WBS 6.4
Liquid Argon Calorimeter System

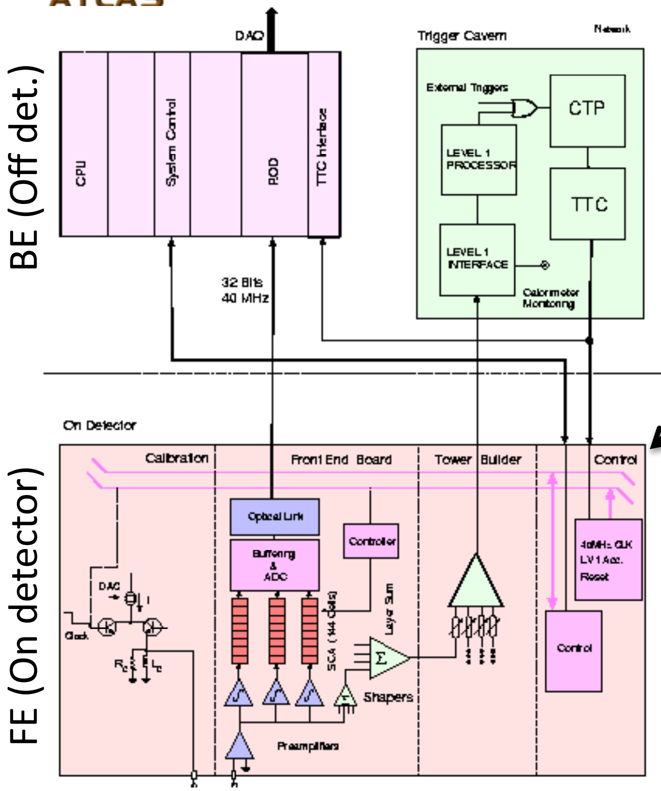
John Parsons
Level-2 Manager
Columbia University

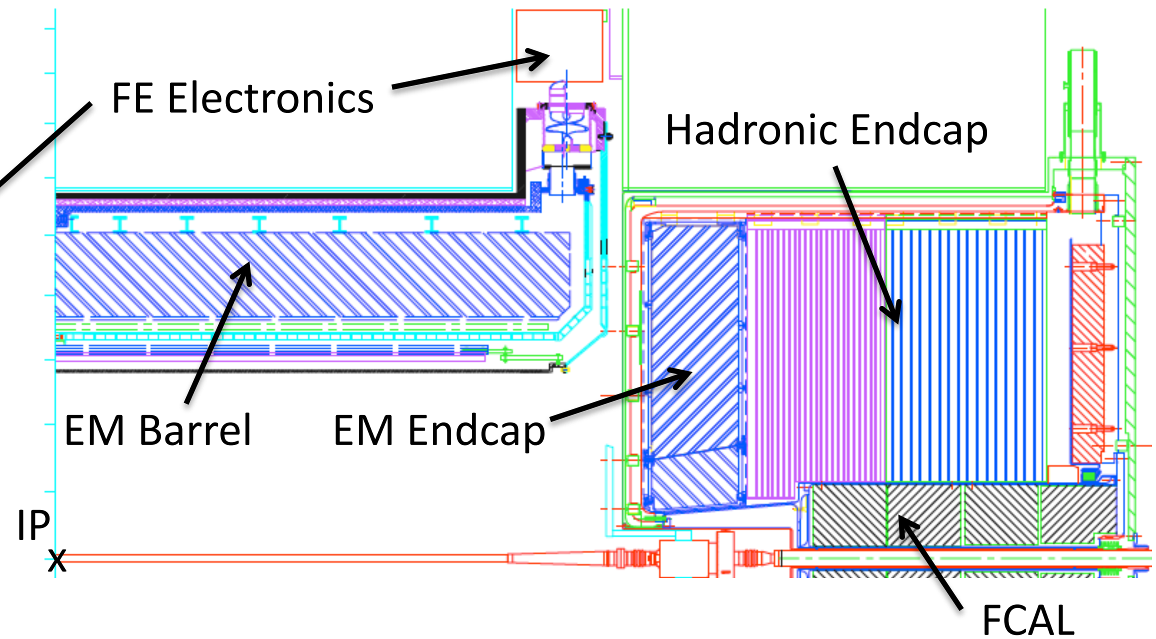
U.S. ATLAS HL-LHC Upgrade Director's Review
Brookhaven National Laboratory
Upton, New York
January 20-22, 2016

Outline

- System Overview
  - Current (Run-2) System and Motivation for Upgrade
  - ATLAS Upgrade Plans
- Proposed U.S. HL-LHC Upgrade Scope
  - Work Breakdown Structure and Contributing Institutes
  - U.S. Deliverables
- Ongoing R&D
  - Plans to Construction Project
- Construction Project Management
  - Construction Project Budget and Schedule
  - Risk, Contingency, and Quality Assurance
- Closing Remarks

LAr Calorimeter System





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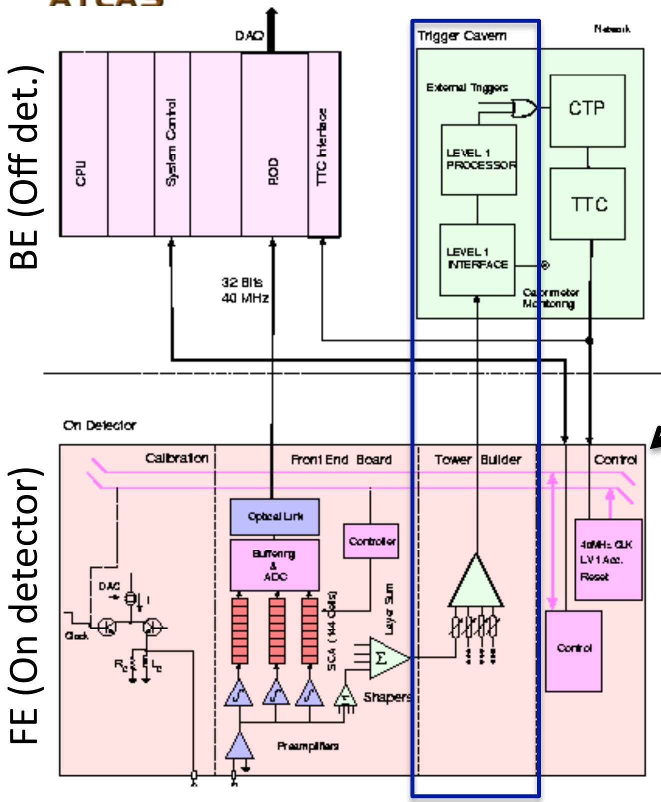
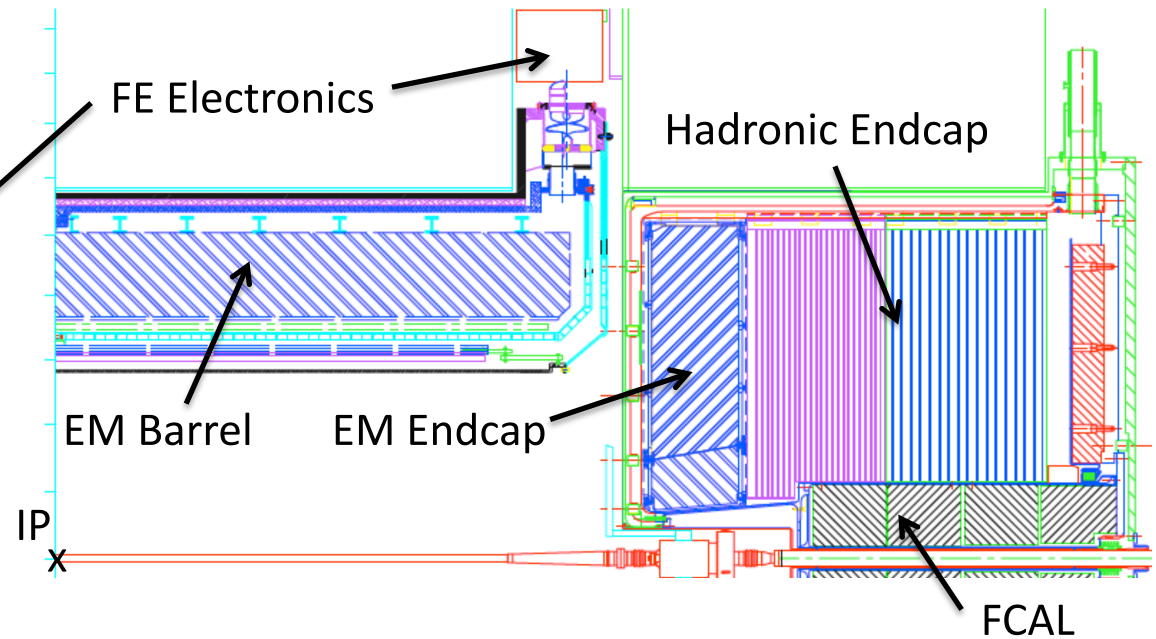


- In Phase I, upgrading L1 trigger electronics to be able to cope with lumi of 2E34



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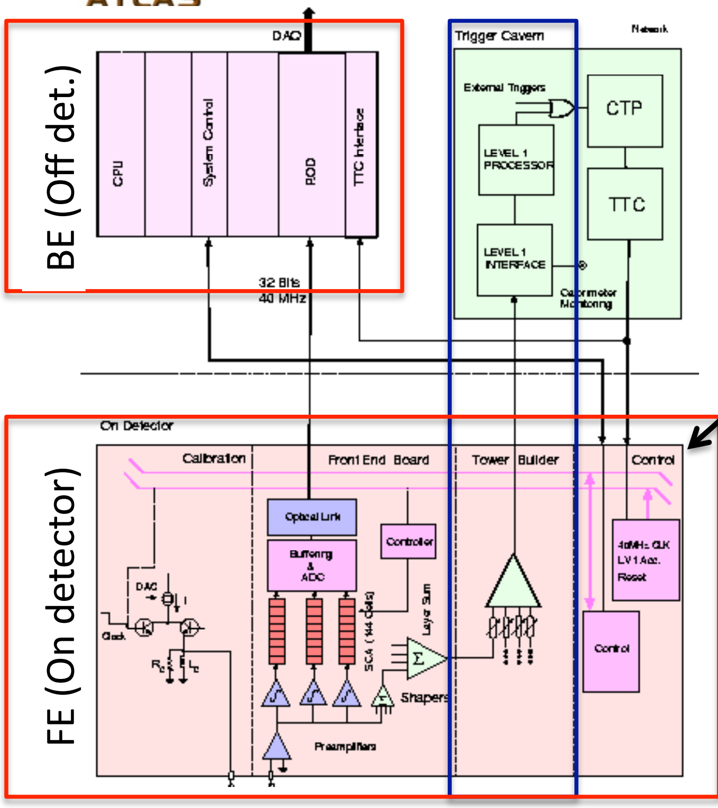

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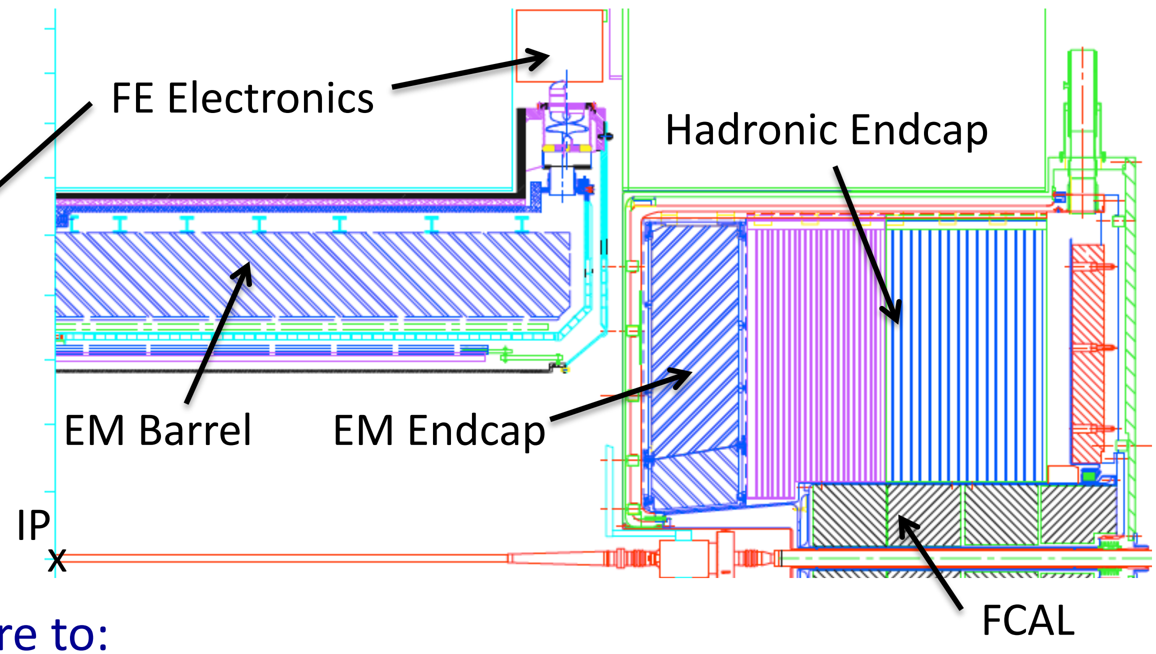

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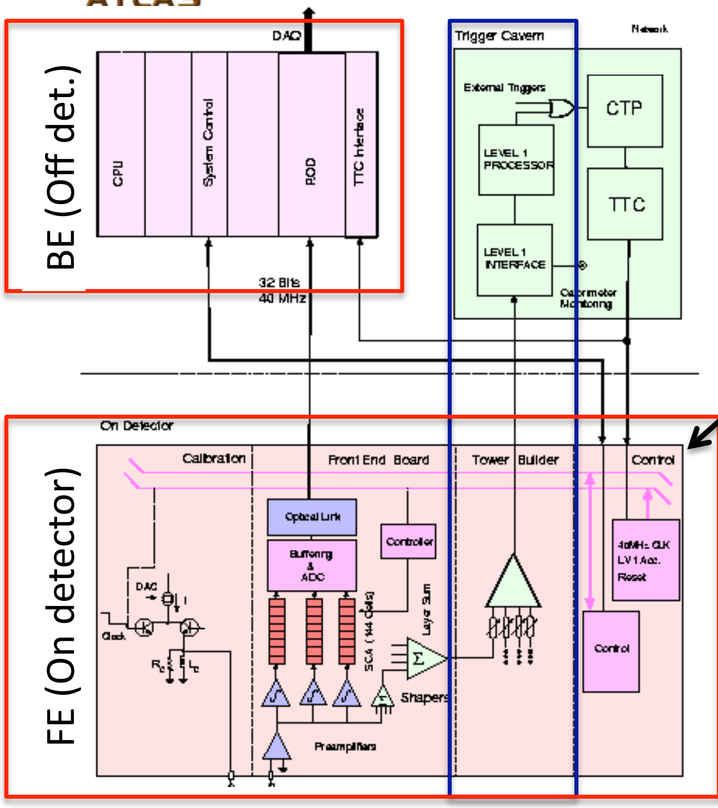
  - Replace LAr readout electronics, both front-end (FE) and back-end (BE)

LAr Calorimeter System



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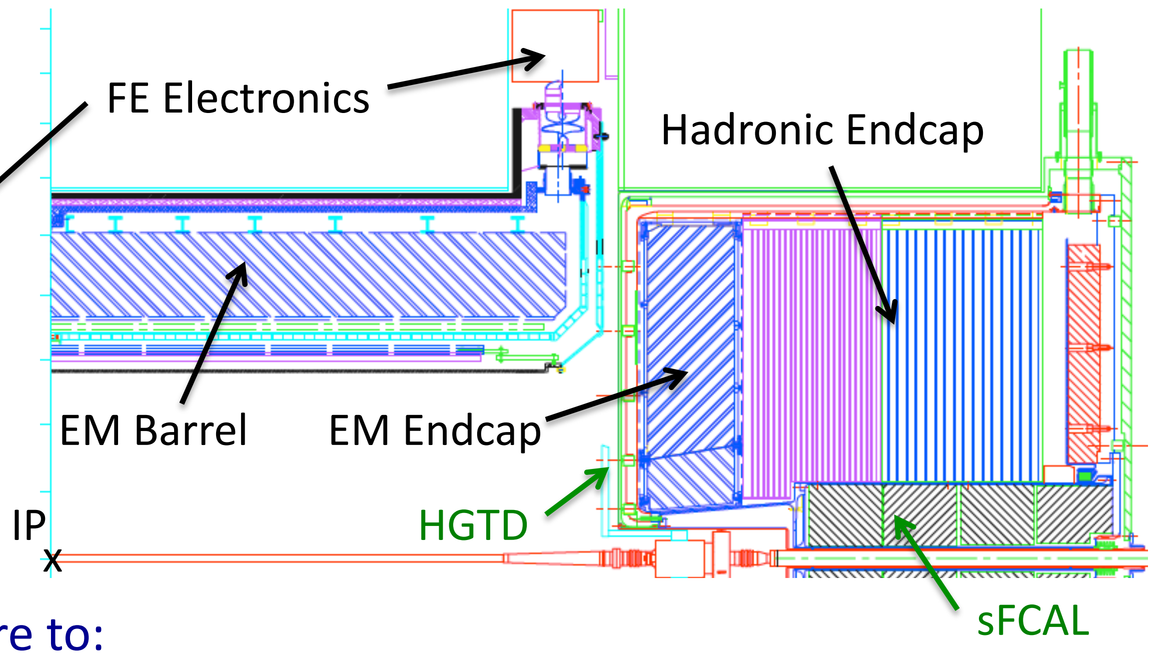


- LAr HL-LHC upgrade plans are to:
  - Replace LAr readout electronics, both front-end (FE) and back-end (BE)
  - Possibly modify the forward region, with options including
    - Possible new sFCAL to replace FCAL (or possible MiniFCAL in front of FCAL)
    - Possible high-granularity timing detector (HGTD) in front of endcap cryostat

LAr HL-LHC Upgrade Motivation

Electronics

- Current readout satisfies original ATLAS spec's (eg. L1 rate/latency < 100 kHz/to 2.5 μs)
- To adopt HL-LHC TDAQ architecture (eg. L0/L1 trigger rate up to 1 MHz/400 kHz, with latency up to 10 μs/60 μs), MUST replace LAr readout electronics (both FE and BE)
- To maintain ability to trigger on low pT objects (eg. ~20 GeV e/γ) in HL-LHC environment, need to provide more info at earlier trigger levels (eg. use EM shower shape vars at L1)
    - Develop new FE electronics, implementing digitization and readout of FULL granularity (~180k channels, with ~16 bit dynamic range) at 40 MHz
    - Develop new BE electronics to process this data, provide inputs to TDAQ system

Forward Region

- HL-LHC physics (eg. VBF Higgs prod., VBS,) places premium on det. perf. in forward region
- At HL-LHC rates, existing FCAL will suffer degraded performance
    - A number of options being considered, including new sFCAL with thinner LAr gaps, or new MiniFCAL in front of FCAL
    - Also considering a forward "4D" high-granularity timing detector (HGTD), to help with pileup rejection, aid in triggering, improve EM response, …

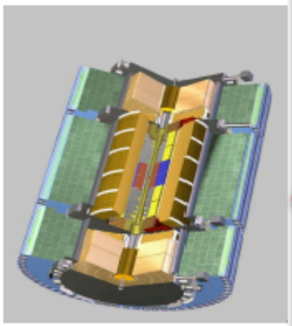
US LAr WBS Structure and Institutions

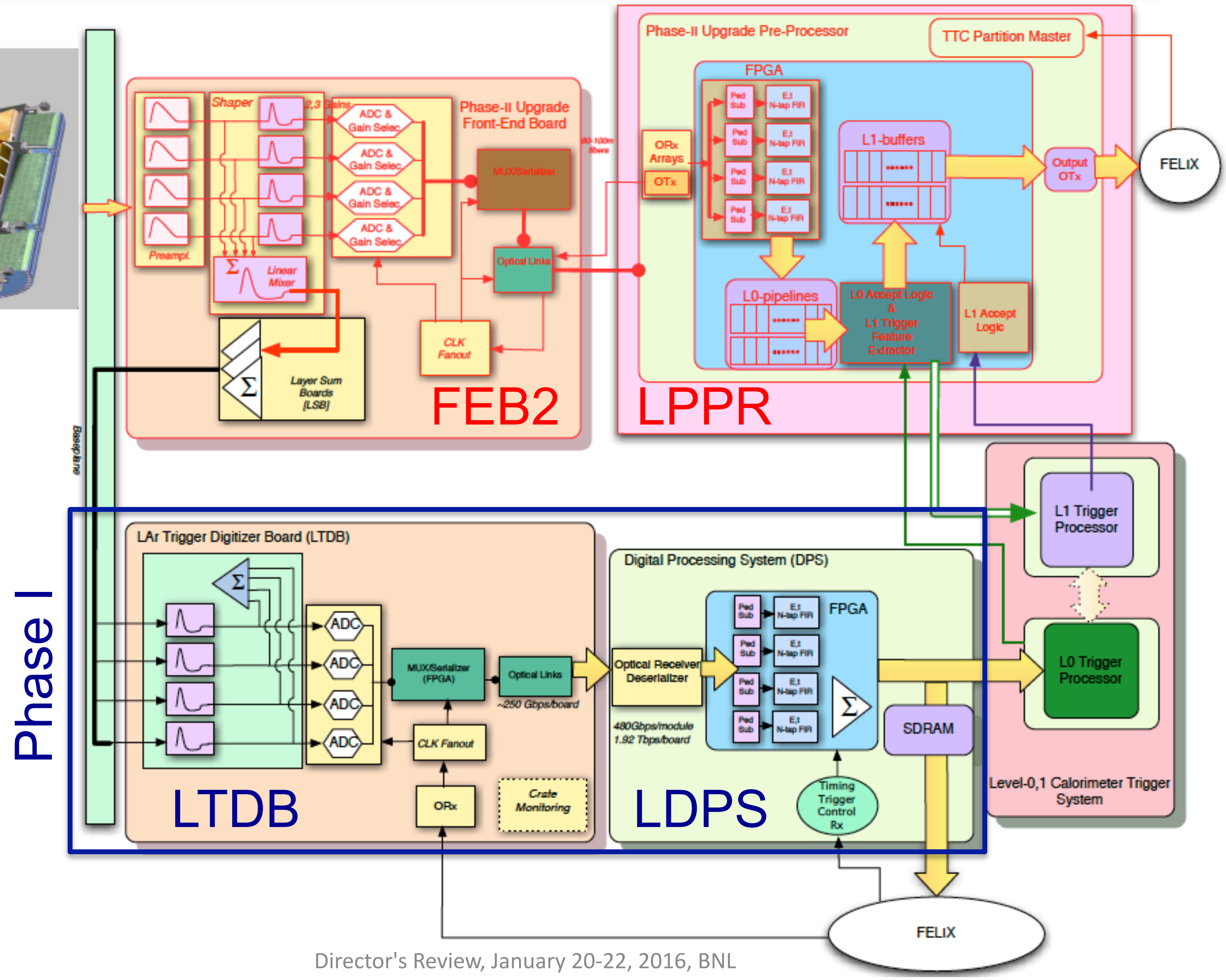
6.4 Liquid Argon WBS (NSF)	
Deliverable/Item	**Institution**
FE Electronics	
6.4.1.1 FE Electronics	Columbia
6.4.2.1 FE Electronics	UT Austin
Optics	
6.4.3.2 Optics	SMU
BE Electronics	
6.4.4.3 BE Electronics	SUNY SB
6.4.5.3 BE Electronics	U Arizona

	6.4 Liquid Argon WBS (DOE)	
	Deliverable/Item	**Institution**
	System Integration	
	6.4.6.4 System Integration	BNL
	PA/Shaper	
	6.4.6.5 PA/Shaper	BNL
	6.4.7.5 PA/Shaper	U Penn
Scope Opportunity	**sFCAL**	
	6.4.5.6 sFCAL	U Arizona
	HGTD	
	6.4.7.7 HGTD	U Penn
	6.4.8.7 HGTD	UCSC
	6.4.9.7 HGTD	SLAC
	6.4.10.7 HGTD	U Iowa

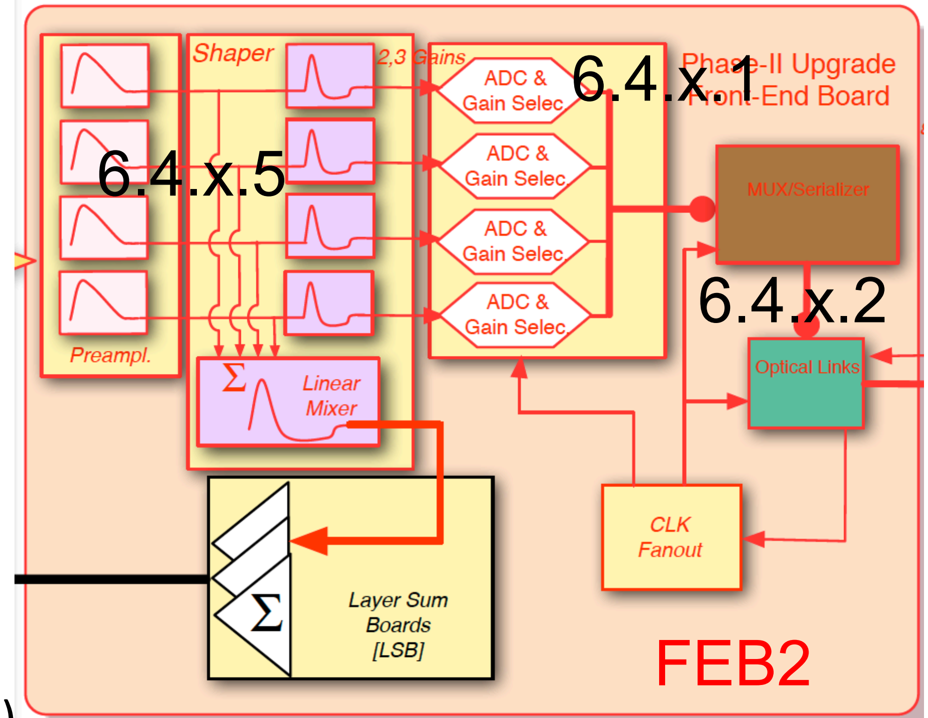
- 8 university groups and 2 labs
- US deliverables organized into 7 BOEs
  - 5 in baseline (3 NSF, 2 DOE)
  - 2 in DOE “Scope Opportunity”

HL-LHC LAr Readout Architecture





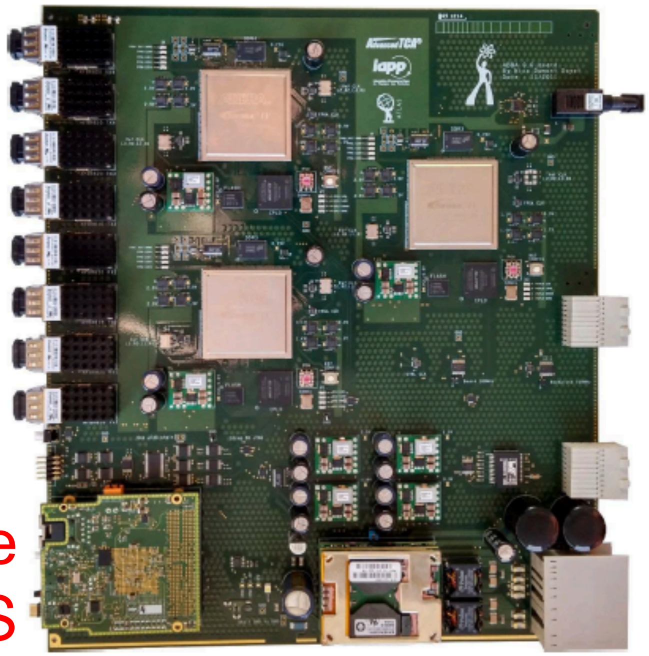
HL-LHC LAr FE Electronics



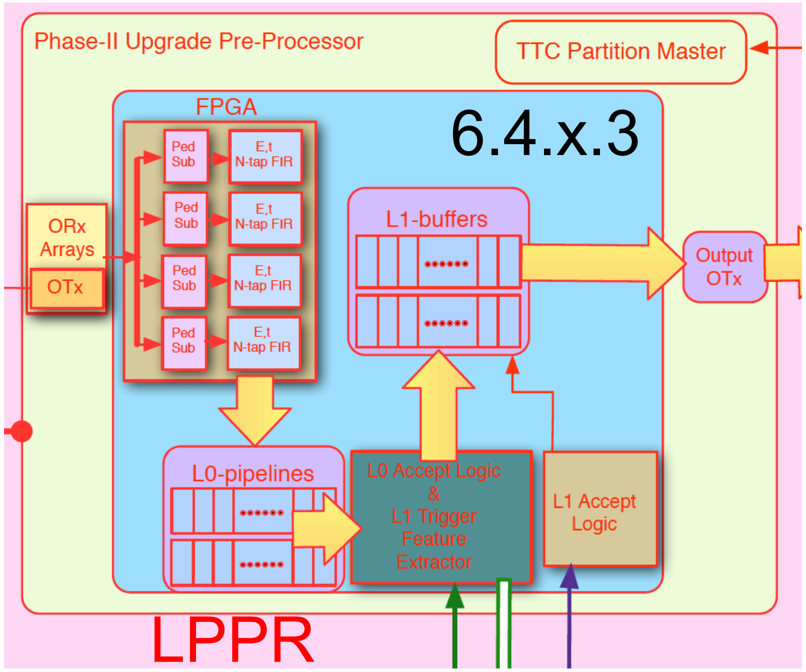
- As in original construction, US groups proposing to take lead responsibility for LAr FE readout electronics, with deliverables including:
  - Radiation-tolerant (65 nm) ASICs
    - Preamp/shaper (BNL, U Penn)
    - 40 MHz ADC (Columbia)
    - 10 Gbps Serializer (SMU)
    - VCSEL array driver (SMU)
  - Optical transmitter (OTx) (SMU)
  - Frontend Board (FEB2) (Columbia)
- WBS items are **6.4.x.1 (FE Electronics), 6.4.x.2 (Optics), 6.4.x.5 (PA/shaper)**
- Apart from complementary French effort on Preamp/shaper, no non-US groups are currently working on these tasks
- Full system requires installation of 1524 FEB2 boards (128 channels each)
  - As in original construction, planning to produce total of 1627

HL-LHC LAr BE Electronics

- LPPR of HL-LHC is natural "evolution" of ATCA-based Phase I LDPS, developed by US groups working with European groups (primarily LAPP Annecy)



Prototype LDPS



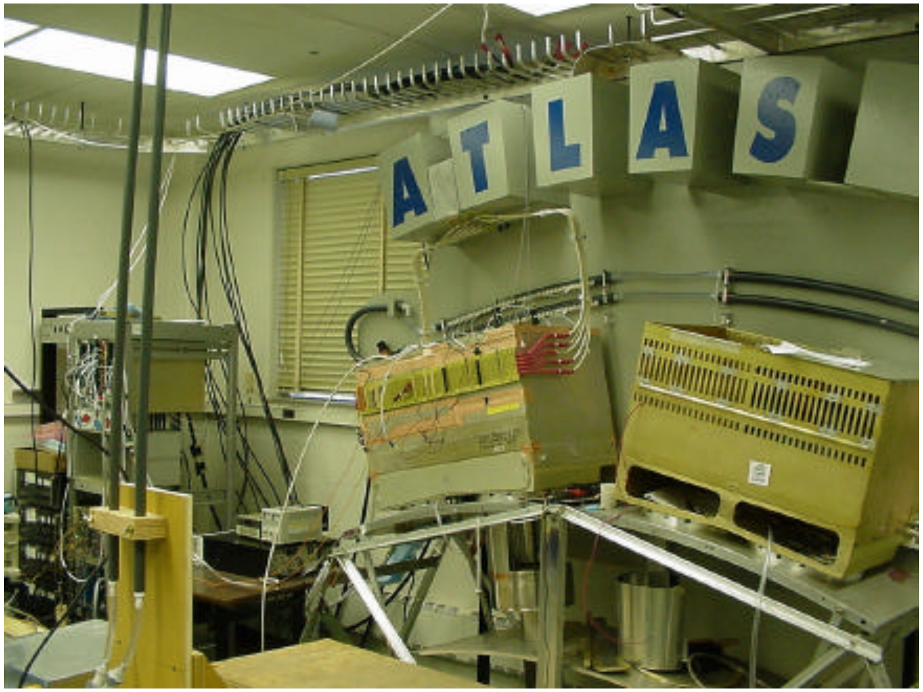
- As in Phase I, US proposes (WBS 6.4.x.3) to take lead responsibility for LPPR motherboard (MB), both hardware and firmware (140 MBs needed in total)
  - SUNY SB – emphasis on hardware
  - U Arizona – emphasis on associated firmware

System Integration

- WBS 6.4.x.4 covers “System Integration” task at BNL, which is part of DOE scope

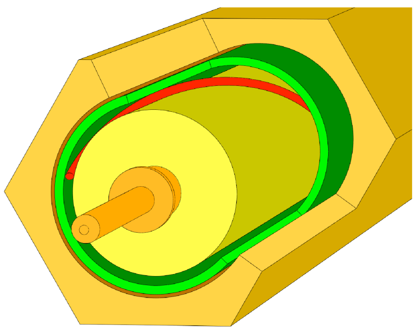
- Work involved includes:
  - Frontend Crate System Test, performed to validate the FE system integration and overall performance before PRRs of the various FE crate boards (including FEB2)
  - Validation and final analog tests of 50% of the FEB2 boards
  - Integration and combined system test of FE and BE electronics

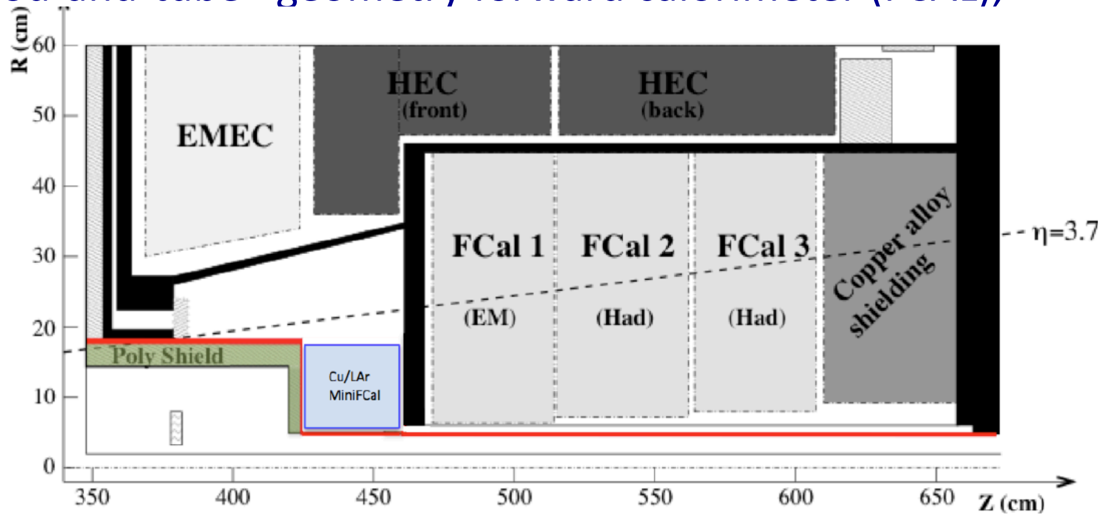
- The equivalent tests were performed at BNL during the original ATLAS construction



sFCAL (WBS 6.4.x.6)

- A novel feature of ATLAS is LAr "rod-and-tube"-geometry forward calorimeter (FCAL), developed by U Arizona group

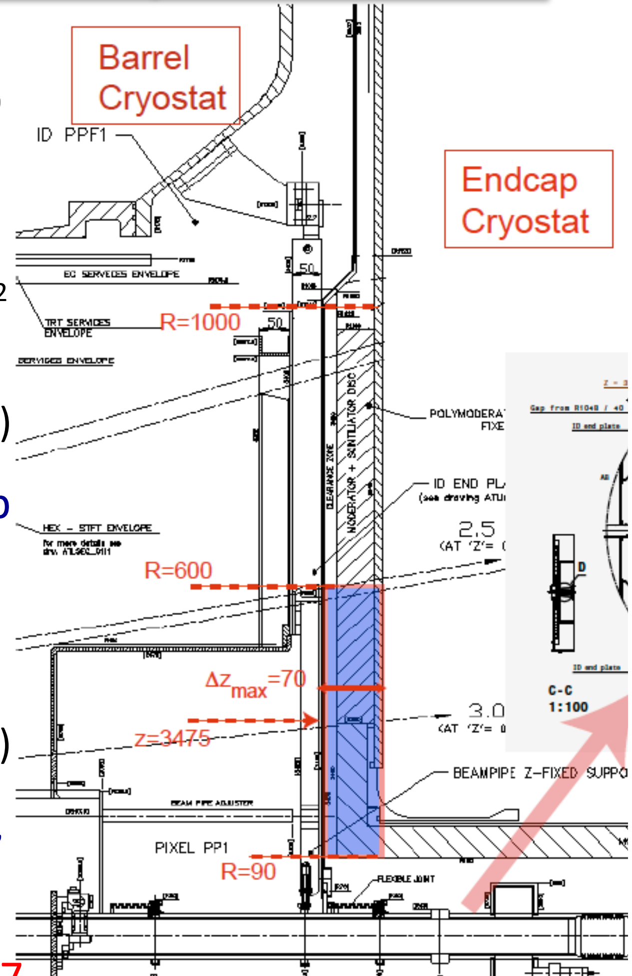




- New sFCAL with thinner gaps (down to 100 μm, instead of 270 – 500 μm) would avoid space charge and other problems in HL-LHC environment
  - sFCAL would also allow finer granularity, and therefore improved performance
  - As for current FCAL, U Arizona to produce sFCAL1 modules, as well as cold electronics
- sFCAL performance needs to be evaluated, and balanced against risks involved in opening cryostats (in pit) to replace FCAL
  - Other options include MiniFCAL in front of FCAL, or doing nothing
  - ATLAS decision about FCAL options planned to be made in June 2016
  - For now, sFCAL (WBS 6.4.x.6) is included in DOE "Scope Opportunity" (~ $5.4M)

High-Granularity Timing Detector HGTD (WBS 6.4.x.7)

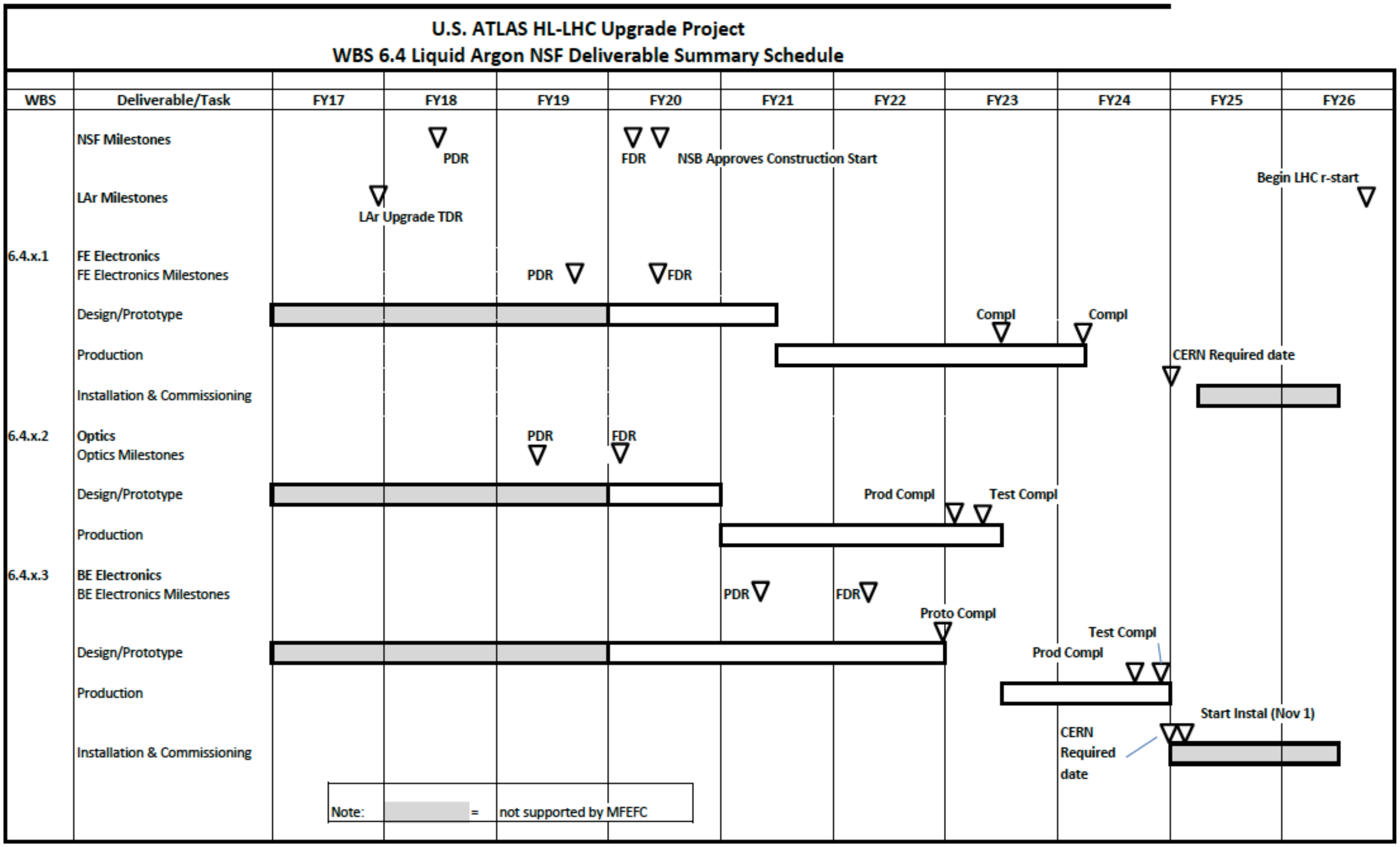
- Possible new "4D" detector in front of EC cryostats
  - Δz = 60 mm detector; |η| range of 2.4 – 4.1 (or even up to 5.0)
- Assuming multiple (eg. 4) layers of Si-based detectors (eg. LGADs developed by UCSC with some CMS collaborators)
  - Want time resolution of 30-50 ps and granularity of 1-100 mm^2
  - Could include absorber plates if also used as preshower
  - Synergies with option of Si/Cu miniFCAL (and also CMS HL-LHC)
- US groups and personnel are providing significant leadership of HGTD, with roles including:
  - Francesco Lanni,BNL (HGTD co-Convenor)
  - Abe Seiden,UCSC (co-Convenor of Detector System group)
  - Ariel Schwartzman,SLAC (co-Convenor of Software&Perf.group)
- Simulation program underway to investigate physics impact,
- In parallel, proceeding with detector development, …
- ATLAS decision whether to build HGTD planned for May 2017
  - Possible US HGTD contribution (WBS 6.4.x.7) included in DOE "Scope Opportunity" (~ $5.3M)



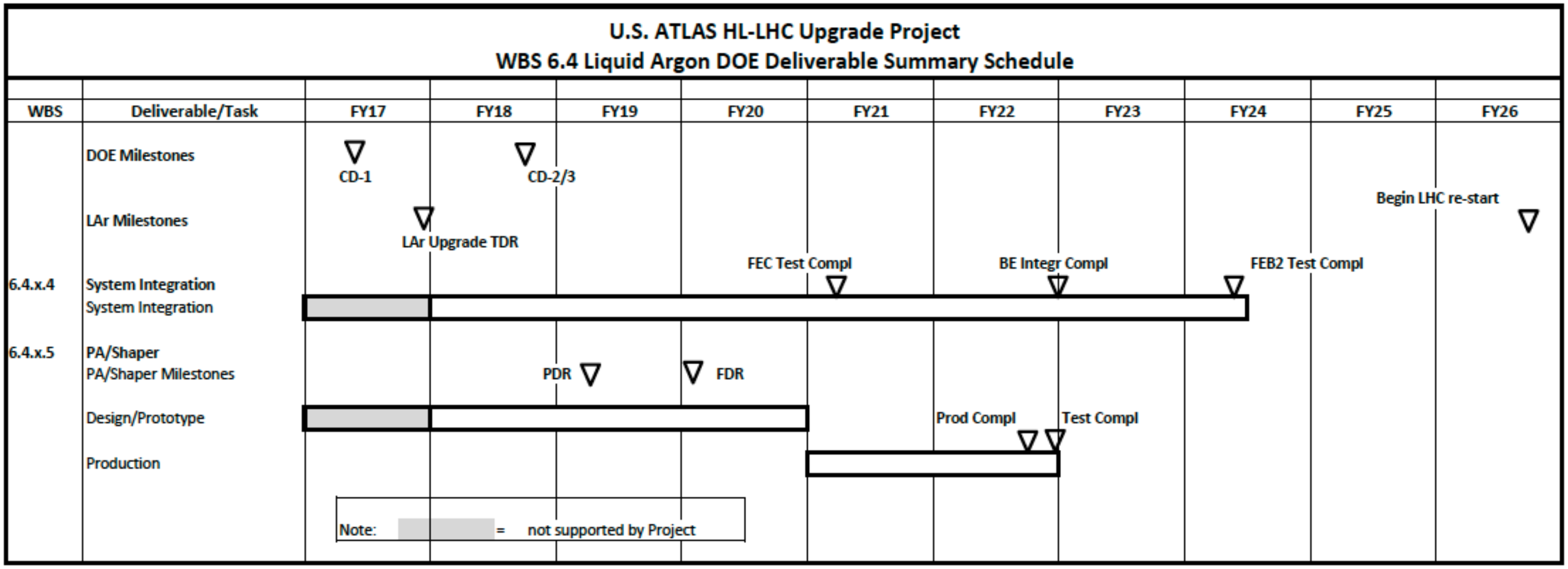
Research & Development

- R&D so far has focused on long-lead items, in particular custom ASIC developments, including:
  - PA/shaper (BNL with U Penn) – 65 nm CMOS, as well as SiGe as backup
  - ADC (Columbia, in collab. with Columbia/UT Dallas EE depts) – 65 nm CMOS
  - Serializer (SMU) – 65 nm CMOS
- In addition, some R&D funding has been used to support ongoing (s)FCAL studies
- Limited R&D budget constrains what can be done before start of MREFC funds (~Q2 FY20), causing some schedule risk
- More details on LAr R&D program and plans will be provided by Hong Ma in breakout session

NSF Schedule & Milestones



DOE Schedule & Milestones



Cost and Effort Estimates

- LAr HL-LHC upgrade cost and effort estimates are detailed in 7 BOEs
  - NSF baseline includes FE Electronics, Optics, BE Electronics
  - DOE baseline includes PA/shaper and System Integration
  - DOE Scope Opportunity includes sFCAL and HGTD

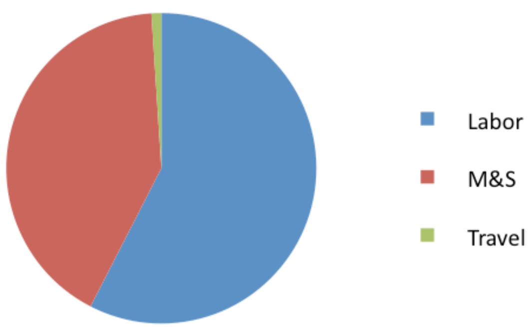
- Given the similarity of our HL-LHC deliverables to our previous ATLAS responsibilities, most cost and manpower estimates are based on our experience with either the original ATLAS construction project or the ongoing ATLAS Phase I upgrade project

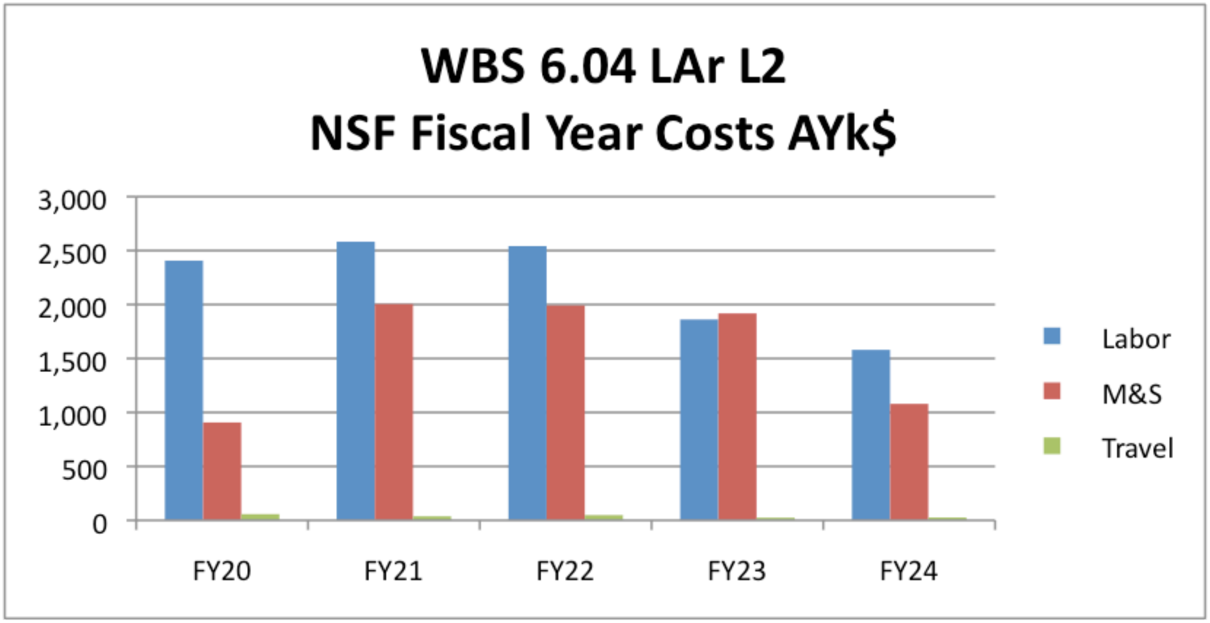
- We assume cost sharing wherein US pays 67% fraction of M&S charges for FEB2 boards, OTx modules, and BE motherboards
  - However, we include 100% M&S costs for all US-led ASIC productions
  - These sharing arrangements are similar as for original ATLAS construction

NSF Budget and Effort

6.04 Liquid Argon NSF Total Cost (AYk$)						
	FY20	FY21	FY22	FY23	FY24	Grand Total
NSF						
Labor	2,407	2,582	2,541	1,862	1,580	10,972
M&S	907	2,005	1,991	1,918	1,079	7,900
Travel	57	37	49	25	26	195
NSF Total	**3,371**	**4,624**	**4,581**	**3,805**	**2,686**	**19,067**

WBS 6.04 LAr NSF Reource Breakdown

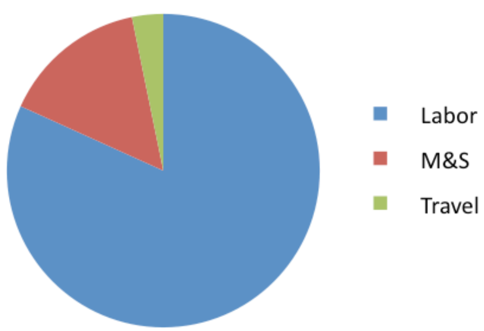


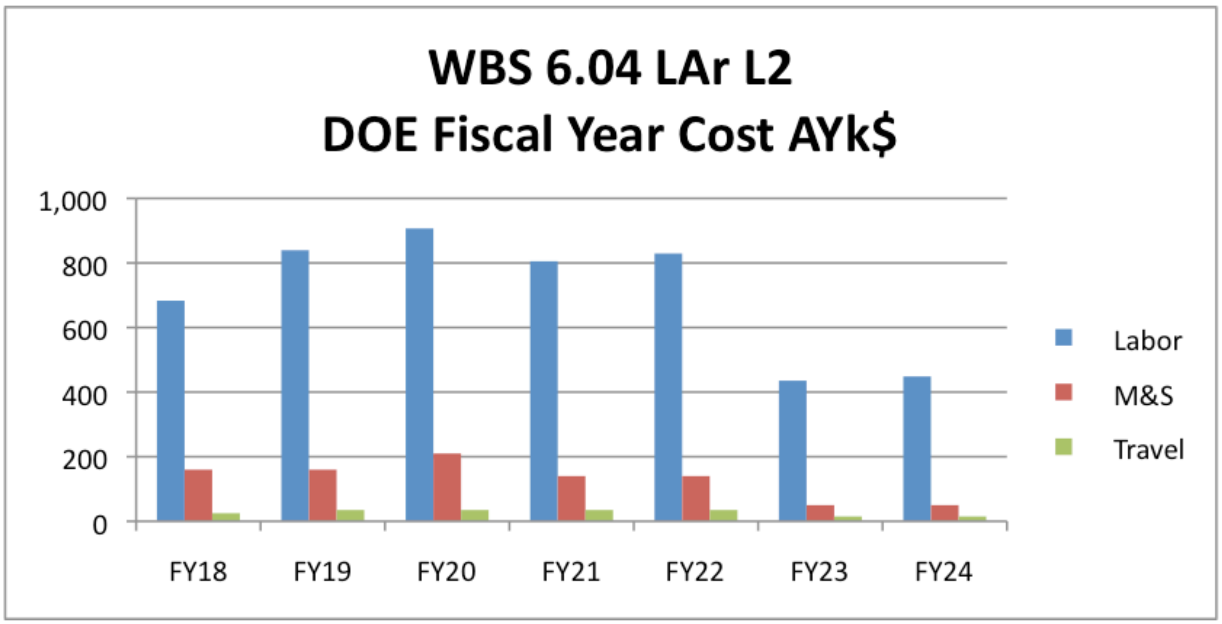


DOE Budget and Effort

6.04 Liquid Argon DOE Total Cost (AYk$)								
	FY18	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
DOE								
Labor	683	839	907	805	829	435	449	4,948
M&S	160	160	210	140	140	50	50	910
Travel	25	35	35	35	35	15	15	195
DOE Total	**868**	**1,034**	**1,152**	**980**	**1,004**	**500**	**514**	**6,053**

WBS 6.04 LAr L2 DOE Resource Breakdown





NSF Cost and Effort (by Deliverable)

6.04 Liquid Argon Total NSF Cost by Deliverable (AYk$)						
Deliverable/Item	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Total**
FE Electronics	**1,451**	**2,595**	**2,758**	**2,232**	**1,378**	**10,414**
6.4.1.1 FE Electronics	1,333	2,474	2,634	2,117	1,260	9,818
6.4.2.1 FE Electronics	119	121	123	115	118	596
Optics						
6.4.3.2 Optics	**991**	**1,115**	**1,116**	**173**	**0**	**3,396**
BE Electronics	**929**	**914**	**708**	**1,399**	**1,308**	**5,258**
6.4.4.3 BE Electronics	765	686	504	1,222	1,182	4,358
6.4.5.3 BE Electronics	164	228	204	177	126	900
NSF Grand Total	**3,371**	**4,624**	**4,582**	**3,805**	**2,686**	**19,067**

6.04 Liquid Argon NSF Total FTEs by Deliverable						
Deliverable/Item	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
FE Electronics	**6.60**	**6.95**	**7.85**	**7.00**	**6.50**	**34.90**
6.4.1.1 FE Electronics	5.60	5.95	6.85	6.00	5.50	29.90
6.4.2.1 FE Electronics	1.00	1.00	1.00	1.00	1.00	5.00
Optics						
6.4.3.2 Optics	**5.25**	**7.00**	**6.95**	**1.00**	**-**	**20.20**
BE Electronics	**4.39**	**4.47**	**4.17**	**3.89**	**3.14**	**20.06**
6.4.4.3 BE Electronics	3.10	3.10	2.80	2.60	2.30	13.90
6.4.5.3 BE Electronics	1.29	1.37	1.37	1.29	0.84	6.16
NSF Grand Total	**16.24**	**18.42**	**18.97**	**11.89**	**9.64**	**75.16**

DOE Cost and Effort (by Deliverable)

6.04 Liquid Argon Total DOE Cost by Deliverable (AYk$)								
Deliverable/Item	FY18	FY19	FY20	FY21	FY22	FY23	FY24	Total
System Integration	**248**	**448**	**464**	**475**	**488**	**500**	**514**	**3,137**
6.4.6.4 System Integration	248	448	464	475	488	500	514	3,137
PA/Shaper	**621**	**586**	**688**	**505**	**516**	**0**	**0**	**2,916**
6.4.6.5 PA/Shaper	439	452	515	417	426	0	0	2,249
6.4.7.5 PA/Shaper	182	135	173	88	90	0	0	667
DOE Grand Total	**868**	**1,034**	**1,152**	**980**	**1,004**	**500**	**514**	**6,053**

6.04 Liquid Argon Total DOE FTEs by Deliverable (k$)								
Deliverable/Item	FY18	FY19	FY20	FY21	FY22	FY23	FY24	Grand Total
System Integration	**1.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**13.00**
6.4.6.4 System Integration	1.00	2.00	2.00	2.00	2.00	2.00	2.00	13.00
PA/Shaper	**2.73**	**2.43**	**2.80**	**2.00**	**2.00**	**-**	**-**	**11.96**
6.4.6.5 PA/Shaper	1.50	1.50	1.50	1.50	1.50	-	-	7.50
6.4.7.5 PA/Shaper	1.23	0.93	1.30	0.50	0.50	-	-	4.46
DOE Grand Total	**3.73**	**4.43**	**4.80**	**4.00**	**4.00**	**2.00**	**2.00**	**24.96**

Risks

HL-LHC Upgrade Project Risk Registry for L2 Systems January 4, 2016			Risk Evaluation (L/M/H)						
WBS	Title	Risk Owner	Cost	Schedule	Scope	Contingency %	Contingency AYK$	Average Risk Score	Identified Risks (See BoEs)
6.4	**Liquid Argon**	**Parsons, John**				**35%**	**8,792**	**4.5**	
6.4.x.1	FE Electronics	Parsons, John	M	M	L	35%	3,645	5.0	*Problems that can only be found at bench test and system integration test may impact project schedule. *Delays in ASIC schedule can lead to assembly schedule delays. *Achieving the required performance might require additioal engineering effort. *Given preliminary nature of FEB2 design, final cost could be higher.
6.4.x.2	Optics	Parsons, John	M	L	L	35%	1,188	3.5	* Delay in lpGBT project may impact ASIC design. *Additional engineering could be effort required for ASIC. * Finding vendor qualified to assemble OTx
6.4.x.3	BE Electronics	Parsons, John	M	M	L	35%	1,840	5.0	*Problems that can only be found at bench teat and system integration test may impact project schedule. *Complexity of board requires complex manufacture and assembly process, needs more iterations. *A vendor part may require an intervention at the level of design of the overall system and some modifications of the assemblies.
6.4.x.4	System Integration	Parsons, John	M	M	L	35%	1,098	5.0	*Problems that can only be found at integration stage may impact project schedule and require modifications to one or more components. *A vendor part may require intervention at the level of design of the overall system and some modificaiotn of the assemblies.
6.4.x.5	PA/Shaper	Parsons, John	M	L	M	35%	1,021	4.5	*Problems that can only be found at bench test and system integration test may impact project schedule, requiring additional engineering work.. *Late delivery of ASICs. *Analog circuits can require multiple submissions due to unfreseen performance or manufacturing issues.

- Leading risks, and mitigation strategies, identified in BOEs
  - Can discuss in breakout sessions

Contingency

Budget Contingency

- For now, 35% budget contingency assigned globally to all LAr deliverables

Scope Contingency

- NSF Scope Contingency
  - Provide less firmware effort for BE MBs (up to ~ $1M)
  - Cover M&S for < 67% of FEB2 boards/OTx modules/BE MBs (up to ~ $1M)
- DOE Scope Contingency
  - Do not provide PA/shaper ASIC (up to ~ $1M)

Scope Opportunity

- NSF Scope Opportunity
  - Cover M&S for > 67% of FEB2 boards/OTx modules/BE MBs (up to ~ $2.4M)
- DOE Scope Opportunity
  - sFCAL, assuming positive ATLAS decision in June 2016 (up to ~ $5.4M)
  - HGTD, assuming positive ATLAS decision in May 2017 (up to ~ $5.3M)
  - Perform final analog testing at BNL of > 50% of FEB2 boards (up to ~ $0.9M)

Closing Remarks

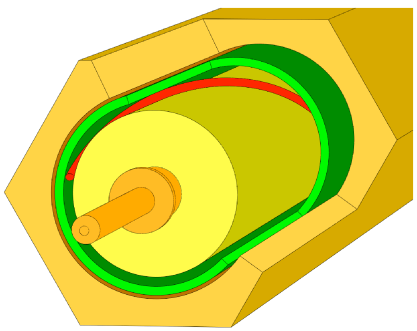
- US HL-LHC deliverables for LAr (as described in a total of 7 BOEs) follow directly from our expertise and experience from:
  - US ATLAS responsibilities of the original ATLAS construction project (FE electronics, Optics, Preamp, System Integration, FCAL)
  - US ATLAS responsibilities of the Phase I Upgrade project (BE electronics)
  - US R&D on very fast Si detectors (HGTD)
- This expertise also provides us with confidence in the budget/effort estimates, which (without contingency) total :
  - $19.1M and 75.2 FTE (NSF, FY20-24)
  - $6.1M and 25.0 FTE (DOE, FY18-24)

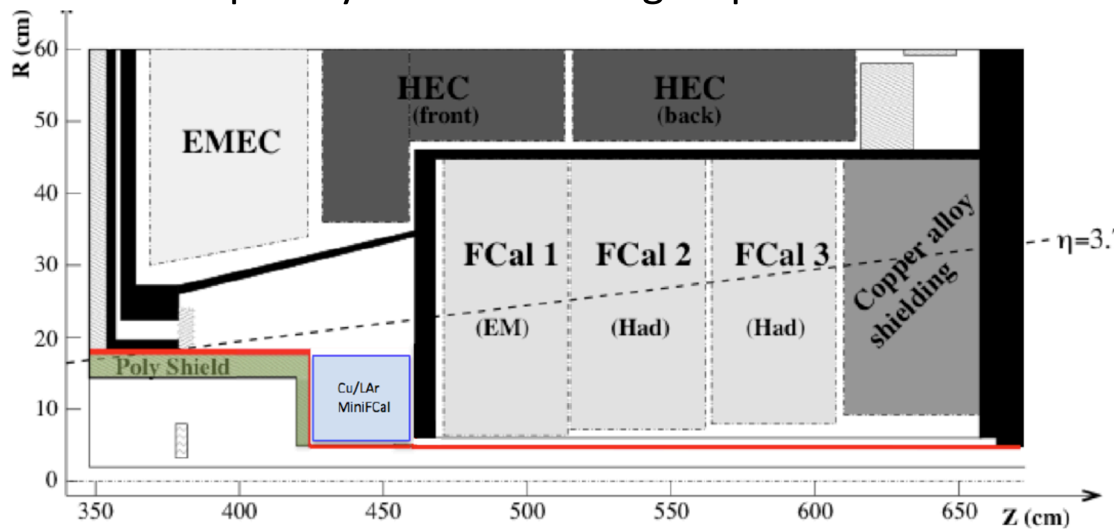
(not including sFCAL and HGTD, which are currently in Scope Opportunity)

Slides for Breakout Session

sFCAL

- A novel feature of ATLAS is its LAr forward calorimeter (FCAL), using a rod-and-tube geometry and integrated into the same cryostat as the other (EM and hadronic) endcap calorimeters
  - This innovative design was developed by the U Arizona group



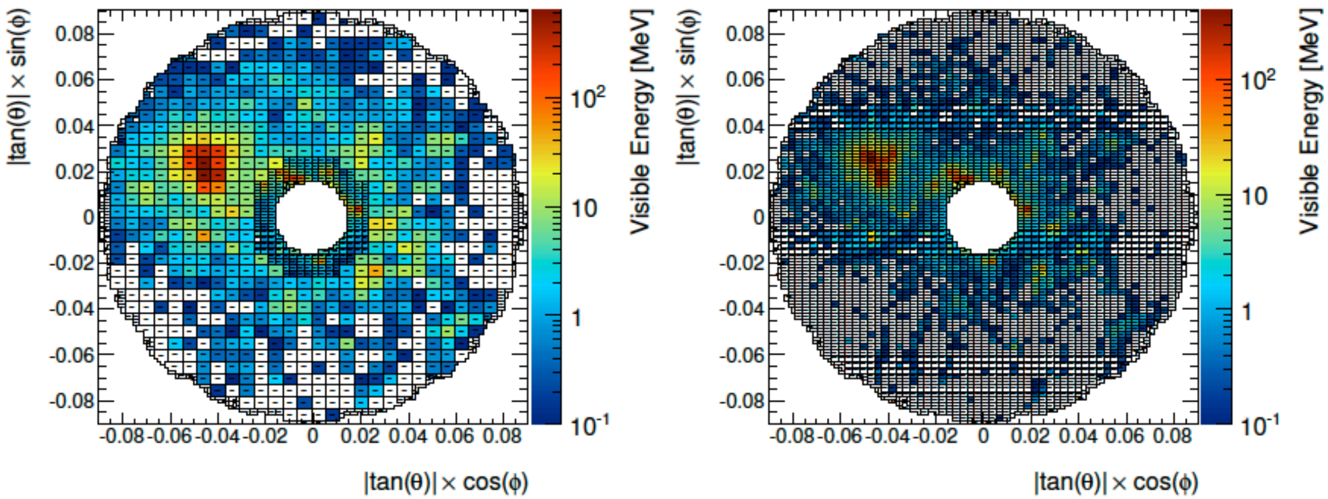


- New sFCAL with thinner gaps (down to 100 μm, instead of 270 – 500 μm) would avoid space charge and other problems in HL-LHC environment

- As for original FCAL, U Arizona proposes to produce sFCAL1 modules, as well as cold electronics for all sFCAL modules

sFCAL Planning

- sFCAL would also allow finer granularity, and therefore improved performance, in forward region

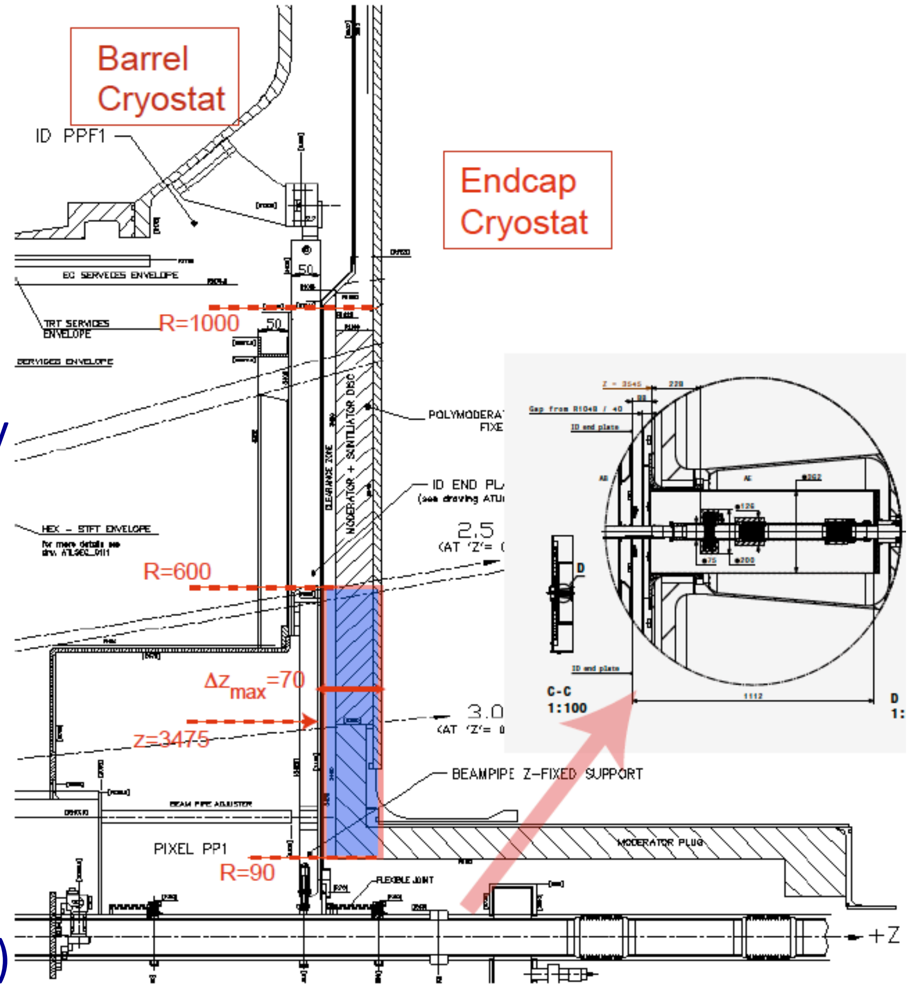


  - Simulations underway to evaluate impact (eg. on jet substructure in VBS)

- sFCAL performance needs to be evaluated, and balanced against risks involved in opening cryostats (in pit) to replace FCAL
  - Other options include MiniFCAL in front of FCAL, or doing nothing
  - ATLAS decision planned to be made by June 2016
  - For now, sFCAL (WBS 6.4.x.6) is included in DOE "Scope Opportunity"

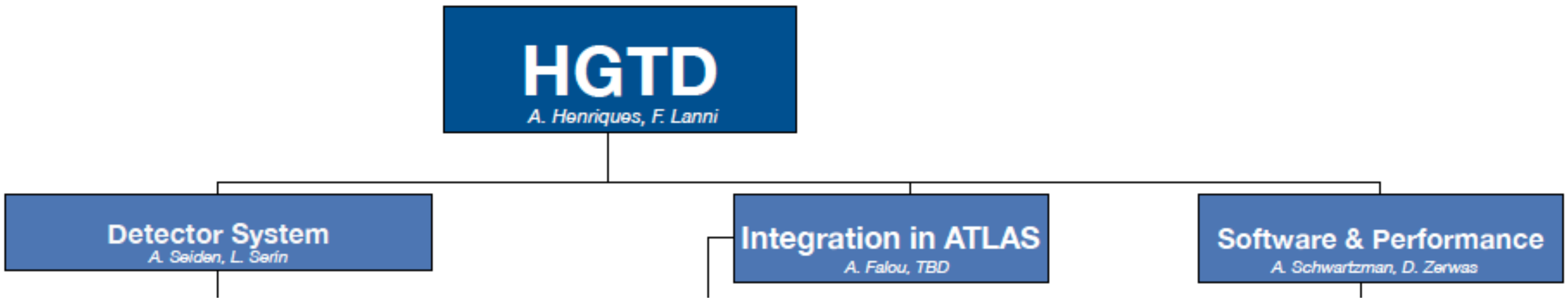
High-Granularity Timing Detector (HGTD)

- Possible new "4D" detector in space of current MTBS (trigger scintillators)
  - Δz = 60 mm detector could cover $|\eta|$ range of 2.4 – 4.1 (or even up to 5.0)
- Assuming multiple (eg. 4) layers of Si-based detectors (eg. LGADs developed by UCSC with some CMS collaborators)
  - Aiming for time resolution of 30-50 ps and spatial granularity of 1-100 mm^2
- Could include absorber if also used as preshower in front of EMEC calorimeter
- Possible synergies with option of Si/Cu miniFCAL (and also CMS HL-LHC upgrade)



HGTD Planning

- US groups and personnel are providing significant leadership of HGTD
- US leadership roles in HGTD management structure include:
  - Francesco Lanni of BNL (HGTD co-Convenor)
  - Abe Seiden of UCSC (co-Convenor of HGTD Detector System group)
  - Ariel Schwartzman of SLAC (co-Convenor of HGTD Software & Performance group)



- Simulation program underway to investigate physics impact, including on pileup rejection, triggering, possible use as preshower, …
- In parallel, proceeding with detector development, testbeam plans, …
- ATLAS decision whether to build HGTD planned by May 2017
  - Possible US HGTD contribution (WBS 6.4.x.7) included in DOE "Scope Opportunity"

LAr WBS Structure and Institutions

6.4 Liquid Argon WBS (NSF)	
Deliverable/Item	**Institution**
FE Electronics	
6.4.1.1 FE Electronics	Columbia
6.4.2.1 FE Electronics	UT Austin
Optics	
6.4.3.2 Optics	SMU
BE Electronics	
6.4.4.3 BE Electronics	SUNY SB
6.4.5.3 BE Electronics	U Arizona

6.4 Liquid Argon WBS (DOE)		
	Deliverable/Item	**Institution**
	System Integration	
	6.4.6.4 System Integration	BNL
	PA/Shaper	
	6.4.6.5 PA/Shaper	BNL
	6.4.7.5 PA/Shaper	U Penn
Scope Opportunity	**sFCAL**	
	6.4.5.6 sFCAL	U Arizona
	HGTD	
	6.4.7.7 HGTD	U Penn
	6.4.8.7 HGTD	UCSC
	6.4.9.7 HGTD	SLAC
	6.4.10.7 HGTD	U Iowa

- 8 university groups and 2 labs
- US deliverables organized into 7 BOEs
  - 5 in baseline (3 NSF, 2 DOE)
  - 2 in DOE "Scope Opportunity"

NSF Cost and Effort (by Deliverable)

6.04 Liquid Argon Total NSF Cost by Deliverable (AYk$)						
Deliverable/Item	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Total**
FE Electronics	**1,451**	**2,595**	**2,758**	**2,232**	**1,378**	**10,414**
6.4.1.1 FE Electronics	1,333	2,474	2,634	2,117	1,260	9,818
6.4.2.1 FE Electronics	119	121	123	115	118	596
Optics						
6.4.3.2 Optics	991	1,115	1,116	173	0	3,396
BE Electronics	**929**	**914**	**708**	**1,399**	**1,308**	**5,258**
6.4.4.3 BE Electronics	765	686	504	1,222	1,182	4,358
6.4.5.3 BE Electronics	164	228	204	177	126	900
NSF Grand Total	**3,371**	**4,624**	**4,582**	**3,805**	**2,686**	**19,067**

6.04 Liquid Argon NSF Total FTEs by Deliverable						
Deliverable/Item	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
FE Electronics	**6.60**	**6.95**	**7.85**	**7.00**	**6.50**	**34.90**
6.4.1.1 FE Electronics	5.60	5.95	6.85	6.00	5.50	29.90
6.4.2.1 FE Electronics	1.00	1.00	1.00	1.00	1.00	5.00
Optics						
6.4.3.2 Optics	5.25	7.00	6.95	1.00	-	20.20
BE Electronics	**4.39**	**4.47**	**4.17**	**3.89**	**3.14**	**20.06**
6.4.4.3 BE Electronics	3.10	3.10	2.80	2.60	2.30	13.90
6.4.5.3 BE Electronics	1.29	1.37	1.37	1.29	0.84	6.16
NSF Grand Total	**16.24**	**18.42**	**18.97**	**11.89**	**9.64**	**75.16**

DOE Cost and Effort (by Deliverable)

6.04 Liquid Argon Total DOE Cost by Deliverable (AYk$)								
Deliverable/Item	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Total**
System Integration	**248**	**448**	**464**	**475**	**488**	**500**	**514**	**3,137**
6.4.6.4 System Integration	248	448	464	475	488	500	514	3,137
PA/Shaper	**621**	**586**	**688**	**505**	**516**	**0**	**0**	**2,916**
6.4.6.5 PA/Shaper	439	452	515	417	426	0	0	2,249
6.4.7.5 PA/Shaper	182	135	173	88	90	0	0	667
DOE Grand Total	**868**	**1,034**	**1,152**	**980**	**1,004**	**500**	**514**	**6,053**

6.04 Liquid Argon Total DOE FTEs by Deliverable (k$)								
Deliverable/Item	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
System Integration	**1.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**13.00**
6.4.6.4 System Integration	1.00	2.00	2.00	2.00	2.00	2.00	2.00	13.00
PA/Shaper	**2.73**	**2.43**	**2.80**	**2.00**	**2.00**	**-**	**-**	**11.96**
6.4.6.5 PA/Shaper	1.50	1.50	1.50	1.50	1.50	-	-	7.50
6.4.7.5 PA/Shaper	1.23	0.93	1.30	0.50	0.50	-	-	4.46
DOE Grand Total	**3.73**	**4.43**	**4.80**	**4.00**	**4.00**	**2.00**	**2.00**	**24.96**

6.04 Liquid Argon NSF Total Cost by Phase (AYk$)						
Deliverable/Item/Phase	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
6.4.1 LAr_Columbia	**1,333**	**2,474**	**2,634**	**2,117**	**1,260**	**9,818**
6.4.1.1 FE Electronics	**1,333**	**2,474**	**2,634**	**2,117**	**1,260**	**9,818**
ADC	**802**	**1,348**	**696**	**0**	**0**	**2,846**
Design	0	0	0	0	0	0
Prototype	802	0	0	0	0	802
Production	0	1,348	696	0	0	2,044
FEB	**530**	**1,126**	**1,939**	**2,117**	**1,260**	**6,972**
Design	338	0	0	0	0	338
Prototype	193	631	0	0	0	824
Production	0	494	1,939	2,117	1,260	5,810
6.4.2 LAr_UTAustin	**119**	**121**	**123**	**115**	**118**	**596**
6.4.2.1 FE Electronics	**119**	**121**	**123**	**115**	**118**	**596**
Design	0	0	0	0	0	0
Prototype	119	121	0	0	0	240
Production	0	0	123	115	118	356
6.4.3 LAr_SMU	**991**	**1,115**	**1,116**	**173**	**0**	**3,396**
6.4.3.2 Optics	**991**	**1,115**	**1,116**	**173**	**0**	**3,396**
Serializer	**601**	**550**	**337**	**0**	**0**	**1,488**
Design	0	0	0	0	0	0
Prototype	601	0	0	0	0	601
Production	0	550	337	0	0	887
VCSEL array driver	**171**	**41**	**42**	**0**	**0**	**254**
Design	0	0	0	0	0	0
Prototype	171	0	0	0	0	171
Production	0	41	42	0	0	83
Optical Link	**219**	**524**	**736**	**173**	**0**	**1,653**
Design	0	0	0	0	0	0
Prototype	219	0	0	0	0	219
Production	0	524	736	173	0	1,434
6.4.4 LAr_SB	**765**	**686**	**504**	**1,222**	**1,182**	**4,358**
6.4.4.3 BE Electronics	**765**	**686**	**504**	**1,222**	**1,182**	**4,358**
Design	0	0	0	0	0	0
Prototype	765	686	504	0	0	1,955
Production	0	0	0	1,222	1,182	2,404
6.4.5 LAr_Arizona	**164**	**228**	**204**	**177**	**126**	**900**
6.4.5.3 BE Electronics	**164**	**228**	**204**	**177**	**126**	**900**
Design	0	0	0	0	0	0
Prototype	164	228	204	0	0	596
Production	0	0	0	177	126	303
NSF Grand Total	**3,371**	**4,624**	**4,582**	**3,805**	**2,686**	**19,067**

6.04 Liquid Argon DOE Total Cost by Phase (AYk$)								
Deliverable/Item/Phase	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
6.4.6 LAr_BNL	**687**	**900**	**979**	**892**	**914**	**500**	**514**	**5,386**
6.4.6.4 System Integration	**248**	**448**	**464**	**475**	**488**	**500**	**514**	**3,137**
Design	248	448	464	0	0	0	0	1,159
Prototype	0	0	0	475	488	0	0	963
Production	0	0	0	0	0	500	514	1,014
6.4.6.5 PA/Shaper	**439**	**452**	**515**	**417**	**426**	**0**	**0**	**2,249**
Design	439	0	0	0	0	0	0	439
Prototype	0	452	515	0	0	0	0	967
Production	0	0	0	417	426	0	0	843
6.4.7 LAr_Penn	**182**	**135**	**173**	**88**	**90**	**0**	**0**	**667**
6.4.7.5 PA/Shaper	**182**	**135**	**173**	**88**	**90**	**0**	**0**	**667**
Design	182	0	0	0	0	0	0	182
Prototype	0	135	173	0	0	0	0	308
Production	0	0	0	88	90	0	0	178
DOE Grand Total	**868**	**1,034**	**1,152**	**980**	**1,004**	**500**	**514**	**6,053**

BOE Table: FE Electronics

6.4.x.1 LAr FE Electronics						
WBS	**Description**	**Labor FTE**	**Labor Ayk$**	**M&S Ayk$**	**Travel Ayk$**	**TOTAL Ayk$**
6.4.x.1	**LAr FE Electronics**	**34.9**	**5,370**	**4,948**	**95**	**10,414**
	Instr. Physicists	5.6				
	Engineers	14.9				
	Techs	13.4				
	EE PhD Students	1.0				
6.4.1.1	**LArFE_Columbia**	**29.9**	**4,947**	**4,816**	**55**	**9,818**
	Instr. Physicists	5.6				
	Engineers	12.4				
	Techs	10.9				
	EE PhD Students	1.0				
6.4.2.1	**LArFE_UTAustin**	**5.0**	**423**	**133**	**40**	**596**
	Instr. Physicists	-				
	Engineers	2.5				
	Techs	2.5				
	EE PhD Students	-				

BOE Table: Optics

6.4.x.2 LAr Optical Links						
WBS	**Description**	**Labor FTE**	**Labor Ayk$**	**M&S Ayk$**	**Travel Ayk$**	**TOTAL Ayk$**
6.4.3.2	**LAr Optical Links**	**20.20**	**2,374**	**981**	**40**	**3,396**
	Engineers	11.95				
	Techs	2.50				
	Students	7.00				

BOE Table: BE Electronics

6.4.x.3 LAr BE Electronics						
WBS	**Description**	**Labor FTE**	**Labor Ayk$**	**M&S Ayk$**	**Travel Ayk$**	**TOTAL Ayk$**
6.4.x.3	**LAr BE Electronics**	**20.1**	**3,228**	**1,971**	**60**	**5,258**
	Engineers	9.8				
	EE Postdocs	5.0				
	Techs	2.5				
	Students	2.8				
6.4.4.3	**LArBE_StonyBrook**	**13.9**	**2,460**	**1,868**	**30**	**4,358**
	Engineers	8.2				
	EE Postdocs	5.0				
	Techs	0.7				
	Students	-				
6.4.5.3	**LArFE_Arizona**	**6.2**	**767**	**103**	**30**	**900**
	Engineers	1.6				
	EE Postdocs	-				
	Techs	1.8				
	Students	2.8				

BOE Table: System Integration

6.4.x.4 LAr System Integration						
WBS	Description	Labor FTE	Labor Ayk$	M&S Ayk$	Travel Ayk$	TOTAL Ayk$
6.4.6.4	**LAr System Integration**	**13.00**	**2,692**	**350**	**95**	**3,137**
	Engineers	7.00				
	Techs	6.00				
	Students	-				

BOE Table: PA/shaper

6.4.x.5 PA/Shaper						
WBS	Description	Labor FTE	Labor Ayk$	M&S Ayk$	Travel Ayk$	TOTAL Ayk$
6.4.x.5	**PA/Shaper**	**12.0**	**2,256**	**560**	**100**	**2,916**
	Engineers	7.2				
	Techs	3.5				
	MSEE Students	1.3				
6.4.6.5	**PA/Shaper_BNL**	**7.5**	**1,644**	**530**	**75**	**2,249**
	Engineers	5.0				
	Techs	2.5				
	MSEE Students	-				
6.4.7.5	**PA/Shaper_Penn**	**4.5**	**612**	**30**	**25**	**667**
	Engineers	2.2				
	Techs	1.0				
	MSEE Students	1.3				

BOE Table: sFCAL

6.4.x.6 sFCAL						
WBS	**Description**	**Labor FTE**	**Labor Ayk$**	**M&S Ayk$**	**Travel Ayk$**	**TOTAL Ayk$**
6.4.5.6	**sFCAL**	**18.90**	**1,631**	**3,645**	**81**	**5,357**
	Engineers	8.65				
	Techs	3.25				
	Students	7.20				

BOE Table: HGTD

6.4.x.7 High Granularity Timing Detector (HGTD)						
WBS	Description	Labor FTE	Labor Ayk$	M&S Ayk$	Travel Ayk$	TOTAL Ayk$
6.4.x.7	**HGTD**	**28.11**	**3,474**	**1,604**	**210**	**5,287**
	Engineers	6.86				
	Techs	11.90				
	MSEE Students	1.35				
	Students	8.00				
6.4.8.7	**HGTD_UCSC**	**10.40**	**715**	**520**	**60**	**1,295**
	Engineers	0.40				
	Techs	6.00				
	Students	4.00				
6.4.7.7	**HGTD_Penn**	**4.41**	**602**	**99**	**25**	**726**
	Engineers	2.16				
	Techs	0.90				
	MSEE Students	1.35				
6.4.9.7	**HGTD_SLAC**	**1.90**	**796**	**786**	**75**	**1,656**
	Engineers	1.90				
	Techs	-				
	Students	-				
6.4.10.7	**HGTD_Iowa**	**11.40**	**1,361**	**200**	**50**	**1,610**
	Engineers	2.40				
	Techs	5.00				
	Students	4.00				

Backup Slides

LAr Electronics Radiation Tolerance

Table 14. Radiation tolerance criteria of the LAr electronics for operation at HL-LHC for a total luminosity of $3000\ \mathrm{fb}^{-1}$, including safety factors for background estimation, given in brackets. For COTS, an additional safety factor of 4 is included in case of production in unknown multiple lots. Furthermore, the ATLAS policy specifies annealing tests that allow reducing the enhanced low dose rate safety-factor to 1, which currently is set to 1.5 for ASICs and 5 for COTS.

	TID [kGy]		NIEL [n_{eq}/cm^2]		SEE [h/cm^2]	
ASIC	0.75	(2.25)	2.0×10^{13}	(2)	3.8×10^{12}	(2)
COTS (multiple lots)	9.9	(30)	8.2×10^{13}	(8)	1.5×10^{13}	(8)
COTS (single-lot)	2.5	(7.5)	2.0×10^{13}	(2)	3.8×10^{12}	(2)
LVPS (EMB and EMEC)	0.58	(30)	9.2×10^{12}	(8)	2.4×10^{12}	(8)
LVPS (HEC)	0.17	(2.25)	4.7×10^{12}	(2)	2.7×10^{11}	(2)

sFCAL Simulations

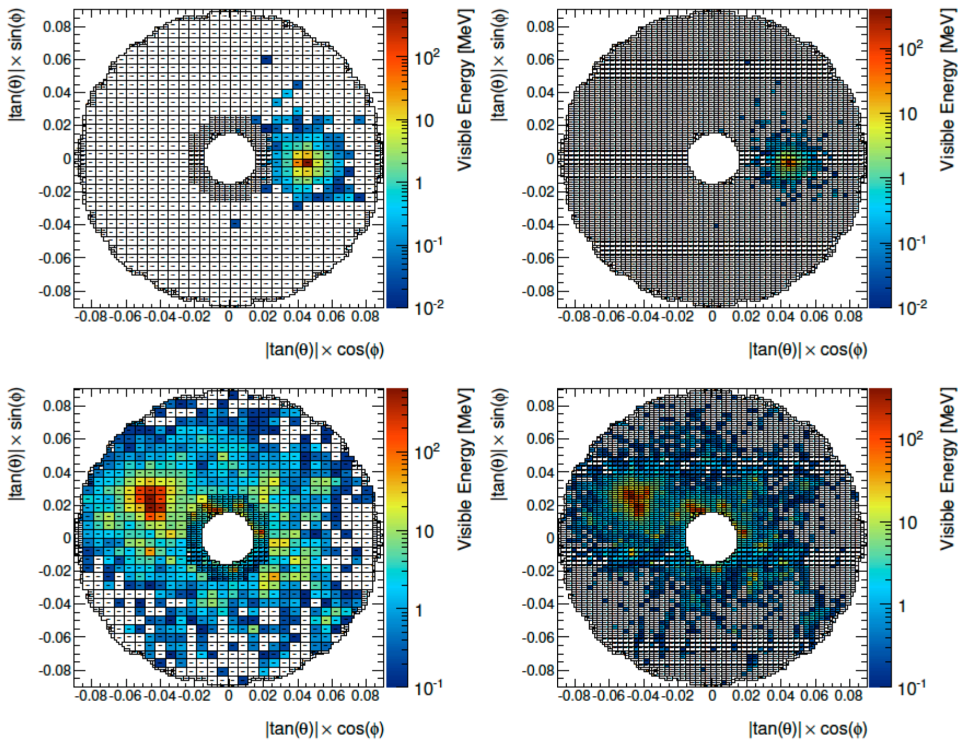


Figure 40. Event displays for the same single electron (upper plots) and the same single jet (lower plots), in the FCal1 (left) and the high-granularity sFCal1 (right).

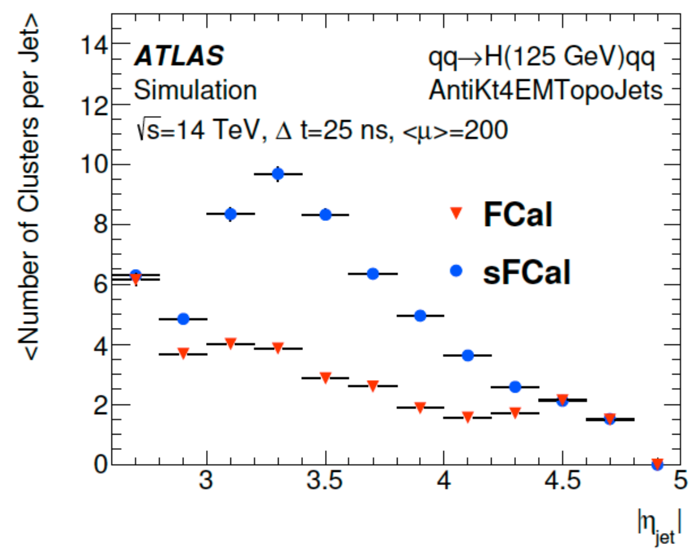
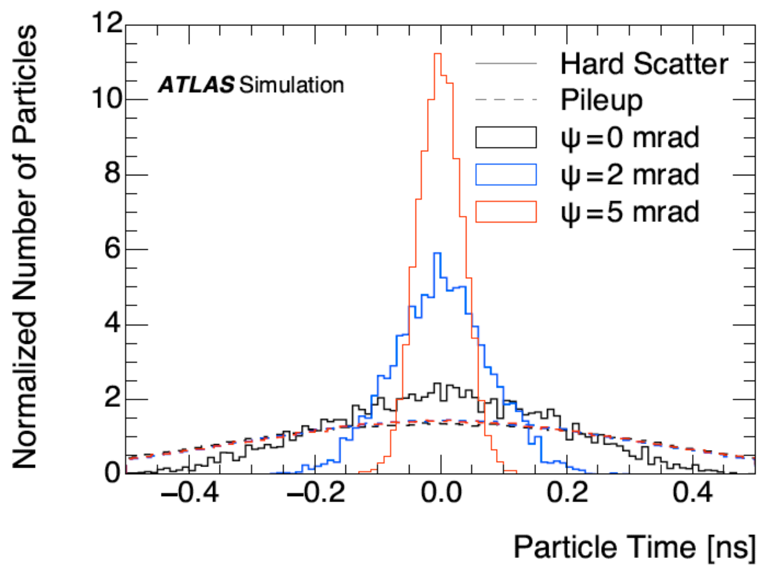


Figure 91. Average number of topo-cluster constituents per VBF tag-jet in the forward region as a function of $|\eta|$. The round dots indicate sFCal+ITk simulations; the triangles FCal+ITk simulations, both with $\mu = 200$. Jets with $R = 0.4$ at the e.m.-scale are matched to outgoing quarks from the VBF production of a 125 GeV mass Higgs boson within $\Delta R = 0.2$. The finer granularity sFCal1 leads to $2-3$ times more constituents in the region $3.2 < |\eta| < 4.3$ which provides better resolution of the substructure inside these jets. This information can be useful to reduce the impact of pile-up, and potentially to assist in distinguishing quark jets from gluon jets.

HGTD Simulations



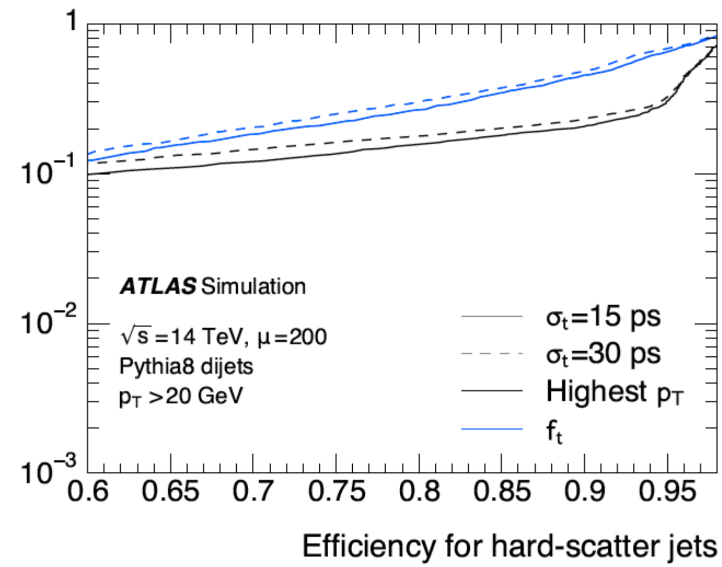
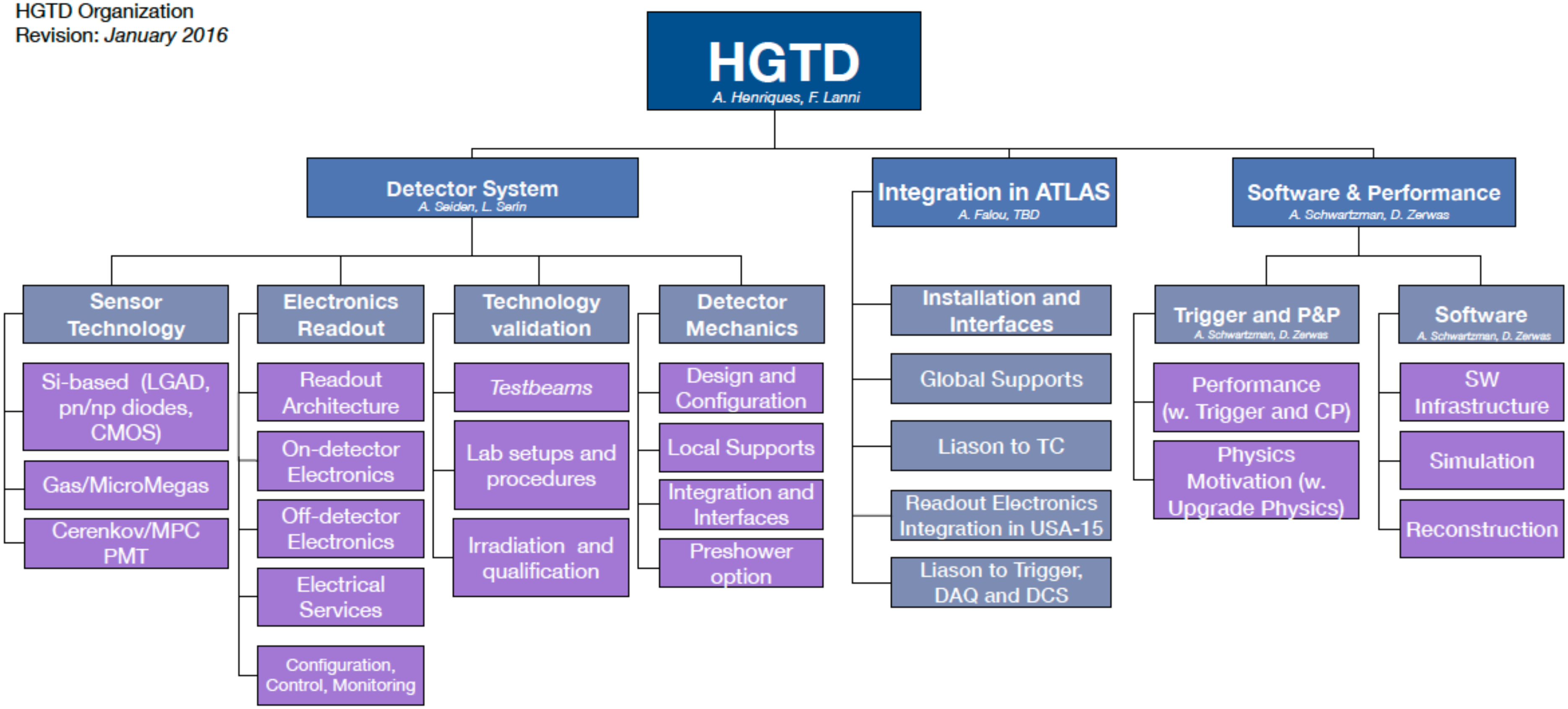


Figure 92. Arrival time spread for hard-scatter and pile-up particles for different bunch collision schemes (crab-kissing angle ψ), assuming that the z position of the hard-scatter vertex is known.

Figure 93. Efficiency for selecting pile-up jets as a function of the efficiency for selecting hard-scatter jets using the jet time from the highest p_T particle (black) and the time fraction f_t (blue) as discriminant, assuming a crab-kissing scheme with $\psi = 5$ mrad.

HGTD Organization Chart

HGTD Organization
Revision: *January 2016*



Scenarios from Scoping Document

Table 25. Top-level summary of the CORE cost estimates for the Phase-II ATLAS upgrades by detector subsystems (expanded to Level-2 in the WBS).

WBS	Detector system	Reference Detector Total Cost [MCHF]	Middle Scenario Differential Cost [MHCF]	Low Scenario Differential Cost [MCHF]
	ATLAS	**271.04**	**-42.55**	**-71.16**
3.	LAr	45.98	-13.60	-13.60
3.1	Read-out electronics	31.39	-	-
3.2	sFCal	10.03	-10.03	-10.03
3.3	HGTD	4.56	-4.56	-4.56
3.4	LAr MiniFCal		*+0.91*	
3.5	Si-based MiniFCal		*+3.57*	

LAr Electronics CORE Costs

WBS ID	Upgrade Item	All Cost Scenarios [kCHF]
3.1	**LAr Readout Electronics**	**31,394**
3.1.1	**LAr Front-end Electronics**	**20,427**
3.1.1.1	Front-end Boards (FEB-2)	9,743
3.1.1.2	Optical fibres and fibre plant	4,306
3.1.1.3	Front-end power distribution system	3,123
3.1.1.4	HEC LVPS	622
3.1.1.5	Calibration System	2,484
3.1.1.6	Shipping and Logistics	150
3.1.2	**LAr Back-end Electronics**	**10,967**
3.1.2.1	LAr Pre-processor Boards (LPPR)	10,212
3.1.2.2	Transition modules	122
3.1.2.3	ATCA shelves	66
3.1.2.4	ATCA switches	76
3.1.2.5	Server PC	22
3.1.2.6	Controller PC	8
3.1.2.7	FELIX/TTC System	460

LAr Electronics Schedule (from SD)

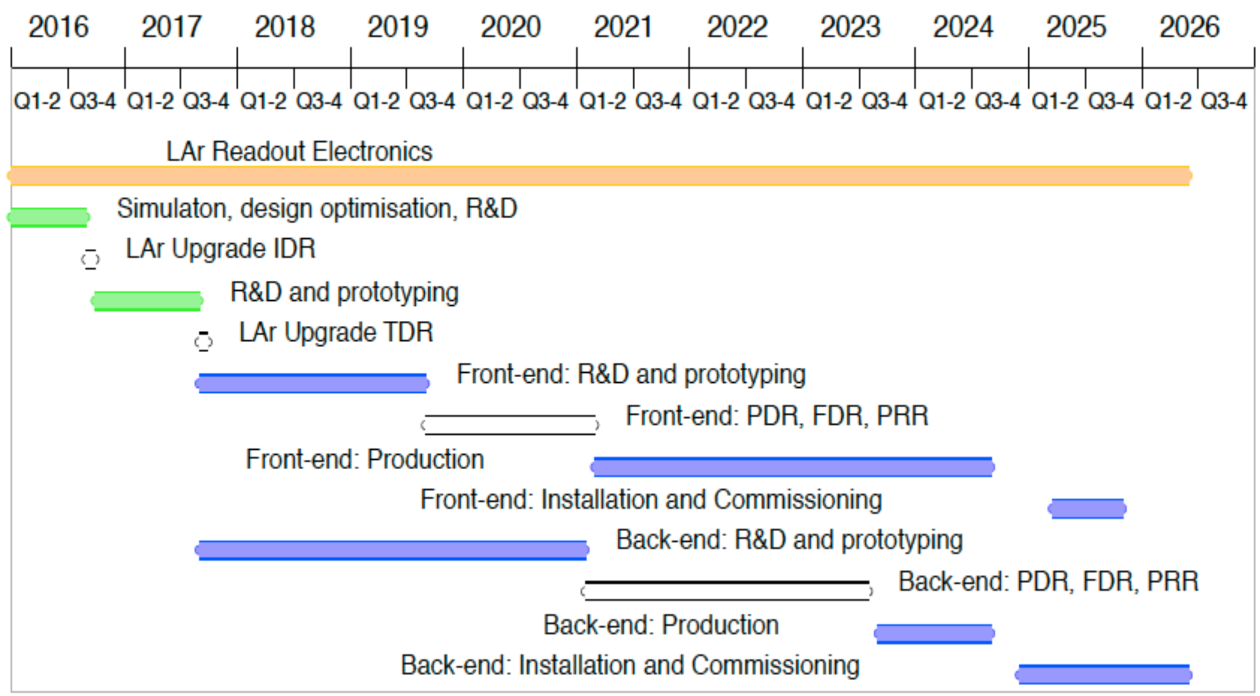


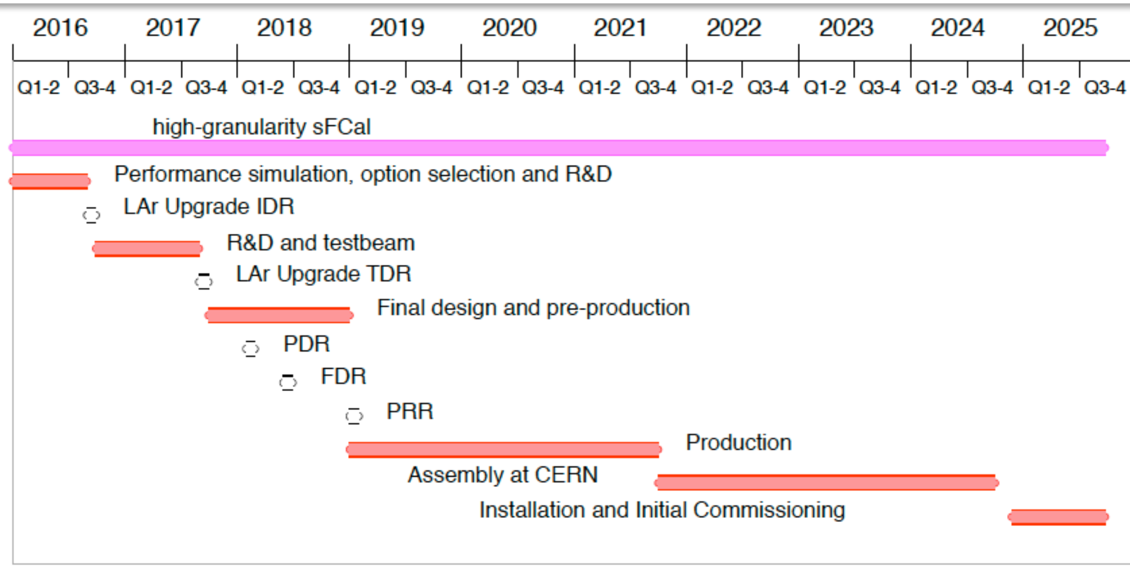
Figure 26. Overview of the time-line and milestones for the main system components of the front-end and back-end systems of the LAr readout electronics upgrade.

sFCAL (MiniFCAL) CORE Costs

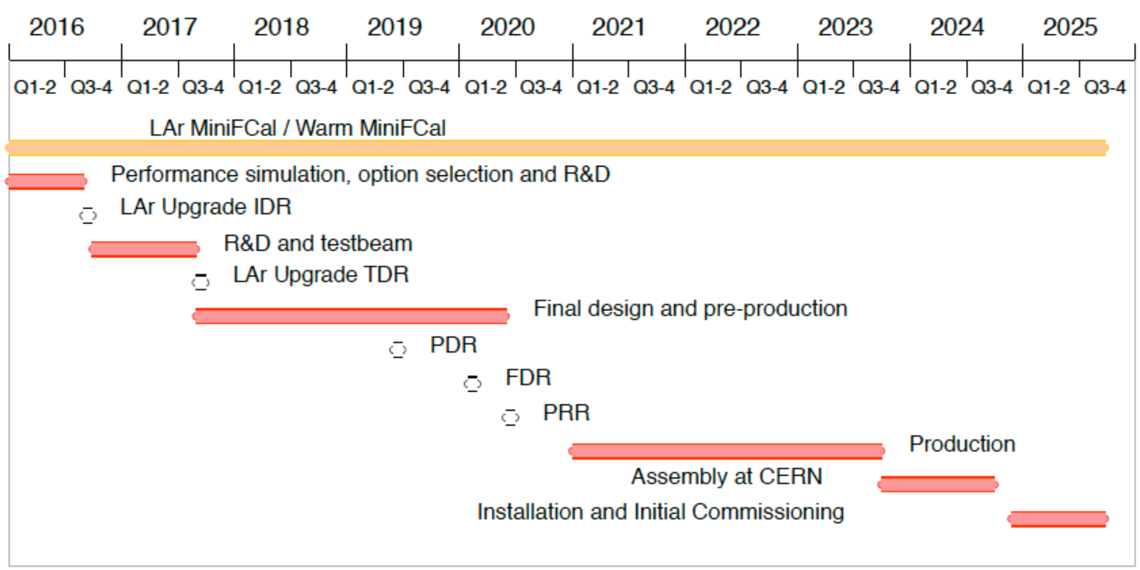
WBS ID	Upgrade Item	Reference [kCHF]	Middle [kCHF]	Low [kCHF]
3.2	**High-granularity sFCal**	**10,033**		
3.2.1	sFCal1	1,381		
3.2.2	sFCal2	2,567		
3.2.3	sFCal3	2,480		
3.2.4	Cold cable harnesses	995		
3.2.5	Plug	115		
3.2.6	Cooling loops	28		
3.2.7	Cryostat modification	399		
3.2.8	Structural tube, cone, bulkhead	118		
3.2.9	Feedthroughs and signal cables	778		
3.2.10	Front-end and back-end electronics	771		
3.2.11	Detector support and tooling	402		
3.4	**LAr/Cu MiniFCal**			**907**
3.4.1	Detector and Cryostat			125
3.4.2	Warm tube, Moderator, Insertion			330
3.4.3	Electronics and HVPS			285
3.4.4	Module 0			167
3.5	**Si/Cu MiniFCal**			**3,573**
3.5.1	Cu absorbers			30
3.5.2	Sensors and on-detector electronics			1,001
3.5.3	Front-end readout			713
3.5.4	Back-end readout			1750
3.5.5	Services			80

sFCAL (MiniFCAL) Schedule (from SD)

sFCAL

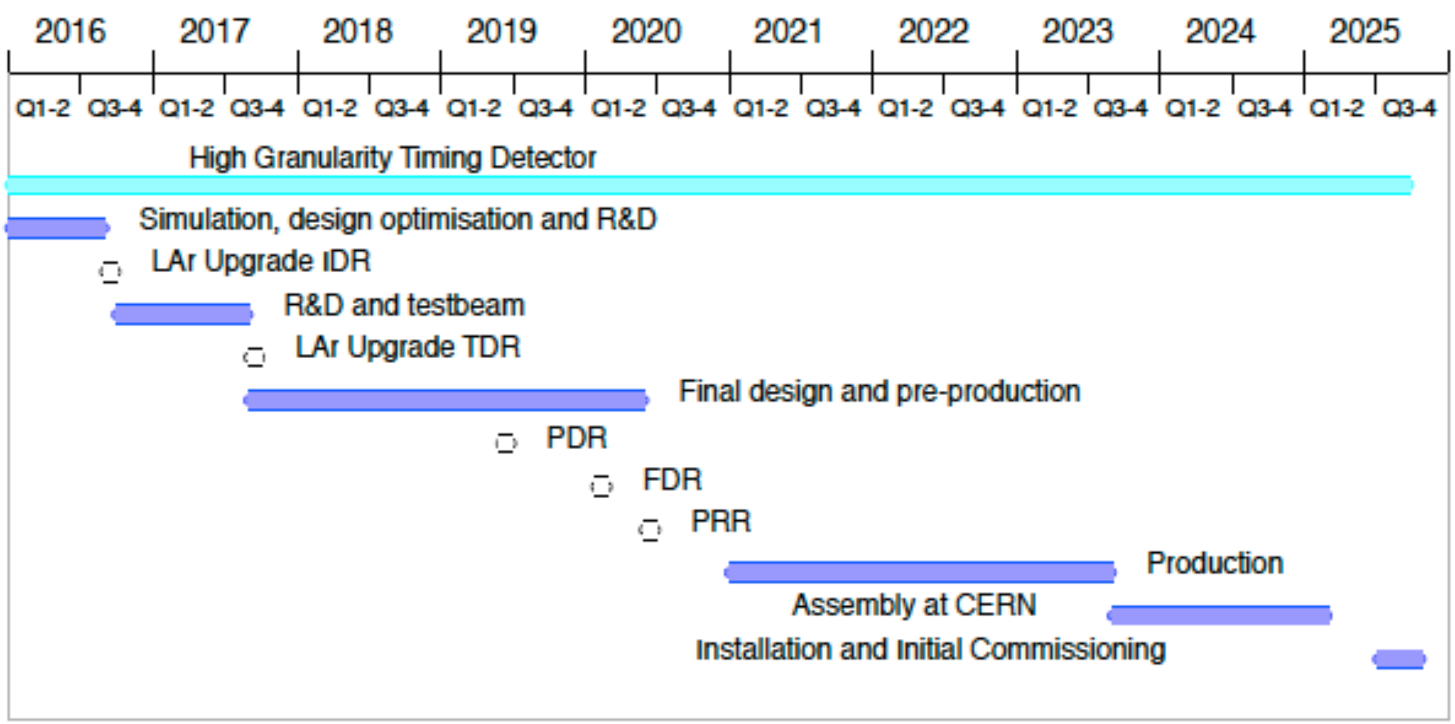


MiniFCAL

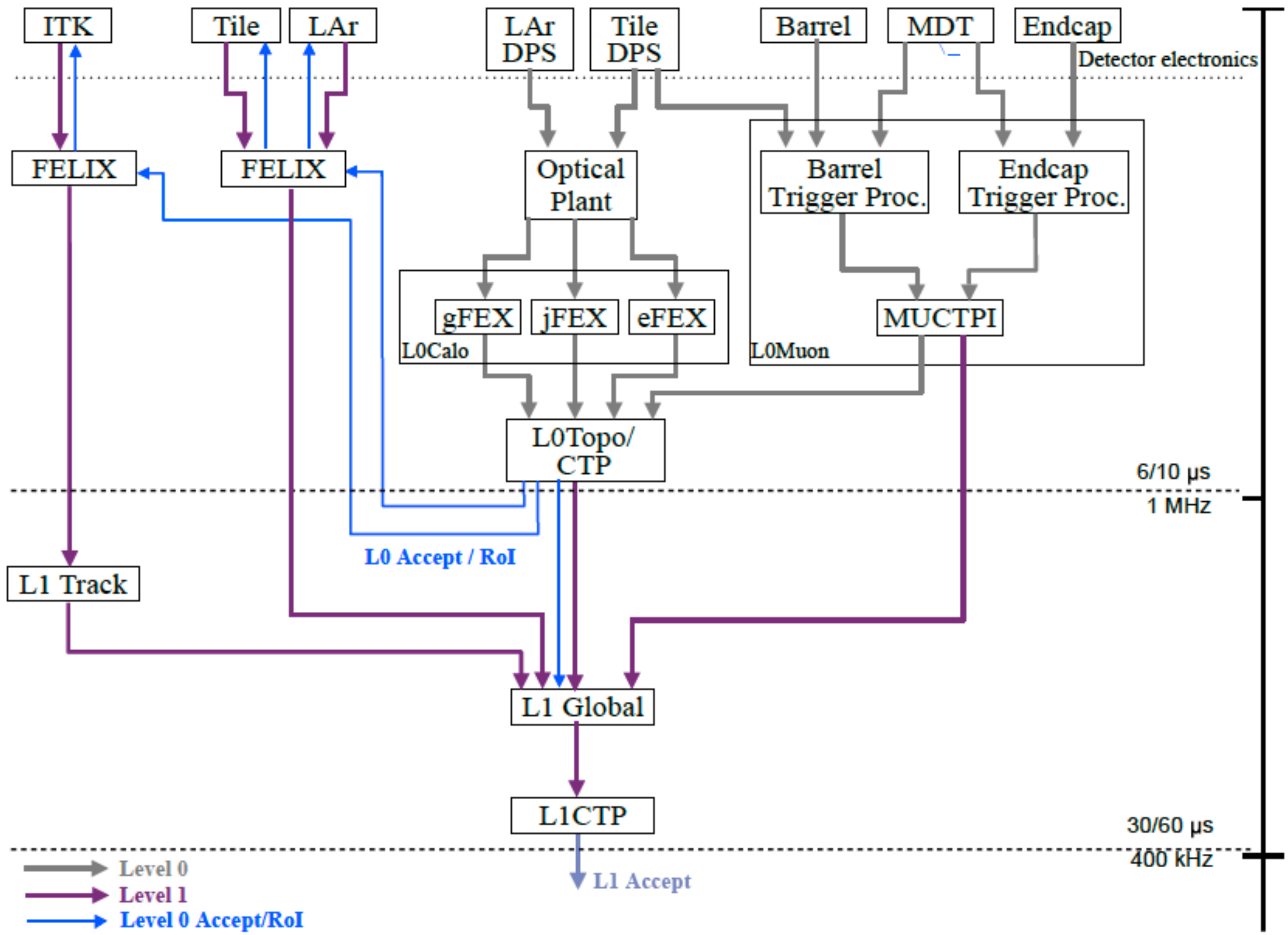


HGTD CORE Costs/Schedule

WBS ID	Upgrade Item	Reference [kCHF]
3.3	**HGTD**	**4,558**
3.3.1	Sensors and on-detector active electronics	1,921
3.3.2	Front-end readout	1,988
3.3.3	Back-end readout	450
3.3.4	Services	200



HL-LHC TDAQ Architecture



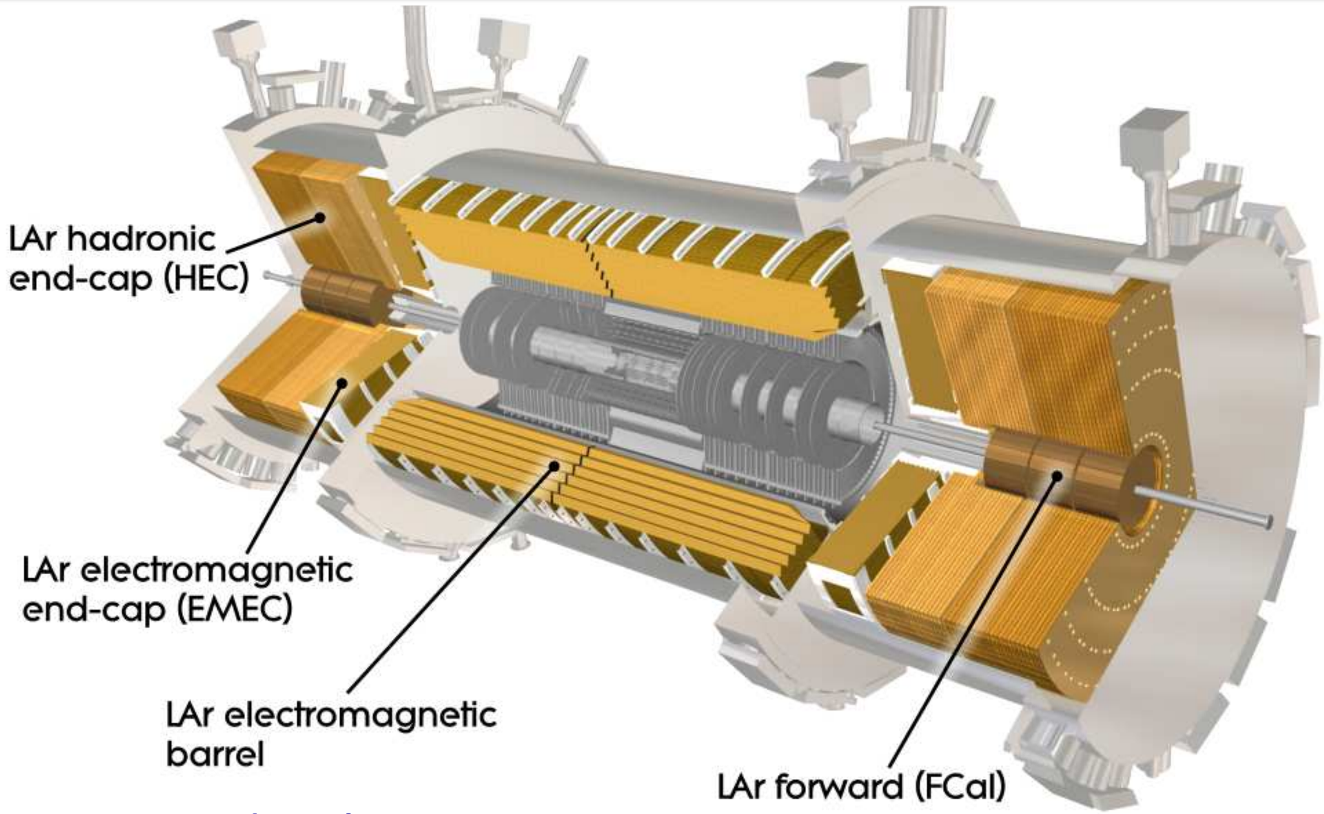
LAr HL-LHC Upgrade Motivation : FE and BE Electronics

- Current LAr readout satisfies original ATLAS specifications, limiting L1 latency to 2.5 μs, max. L1 rate to 100 kHz, …
- To adopt HL-LHC TDAQ architecture (eg. L0/L1 trigger rate up to 1 MHz/400 kHz, with latency up to 10 μs/60 μs), MUST replace LAr readout electronics (both FE and BE)
- To maintain ability to trigger on low pT (~20 GeV) EM objects (e/γ) in high pileup HL-LHC environment, need to provide more info at earlier trigger levels (eg. use EM shower shape vars at L1)
  - Develop new FE electronics, implementing digitization and readout of FULL granularity (~180k channels, with ~16 bit dynamic range) at 40 MHz
  - Develop corresponding new BE electronics to receive and process this data, and provide inputs to TDAQ system

LAr HL-LHC Upgrade Motivation : Forward Region

- HL-LHC physics program (in particular, VBF Higgs production, VBS, …) places a premium on detector performance in the forward region
- At HL-LHC rates, existing FCAL will suffer degraded performance, due to space charge effects, time-dependent HV due to drops across HV resistors, …
  - Also, there are some concerns (being investigated) that there could be LAr boiling
- A number of options being considered:
  1. Replace FCAL with new sFCAL with thinner LAr gaps (to avoid space charge problems), which could have finer granularity for enhanced performance
  2. Place "miniFCAL" in front of existing FCAL, to absorb some of the energy
  3. Do "nothing" and live with degraded FCAL performance
- Also investigating placing a "4D" high-granularity timing detector (HGTD) in front of endcap cryostats, to help with pileup rejection, aid in triggering, improve EM response in forward region, …

LAr Calorimeter System



- LAr HL-LHC upgrade plans are to:
  - Replace LAr readout electronics, both front-end (FE) and back-end (BE)
  - Possibly modify the forward region, with options including
    - Possible new sFCAL to replace FCAL (or possible MiniFCAL in front of FCAL)
    - Possible high-granularity timing detector (HGTD)